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TECHNICAL REPORT 76-11

DECISION ANALYSIS AS AN ELEMENT IN AN OPERATIONAL DECISION AIDING SYSTEM
(Phase III)

by

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Sponsored by

Operational Decision Aids Project
Office of Naval Research (Code 455)
Department of the Navy
Arlington, Virginia 22217

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This paper reports the results of investigations undertaken in a continuing program to develop decision aids for Navy task force commanders. The focus in this contract phase was on the contribution of advanced techniques of decision analysis to action selection situations in the mission execution phase of task force operations. In particular, the investigations centered on testing and refining the prototype interactive computer graphic aid that was identified under a previous contract phase.

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A pilot test of this aid was conducted in order to establish the conceptual acceptability of the aid to operational Navy subjects and to identify areas for aid refinement. In support of the test, the anti-ship missile (ASM) threat was examined and modeled.

Additional investigations were made into methods of enhancing the aid to consider more state hypotheses, to incorporate a model of time, to address a decision maker's attitude toward risk, and to establish a more generalized use of the aid. An initial attempt was also made to establish matching principles between the aid and decision situations existing in the naval tactical environment.

As a result of the pilot test, several modifications and refinements were made to the prototype computer software, and a user's manual is being prepared for support of testbed implementation.

EXECUTIVE SUMMARY

Introduction

This Technical Report summarizes the results of the third phase (FY 76) of research undertaken in support of the Office of Naval Research Operational Decision Aids (ODA) project by Decisions and Designs, Inc. (DDI) of McLean, Virginia. The report represents eight months of research effort in a continuing program in which various technologies, including modern decision analysis, are used to explore the Navy's tactical decision environment for potential applications of their respective methodologies in the form of computer-graphic decision aids. The goal of this research program is the eventual specification of a decision aiding sub-system as an integral part of a higher-order tactical command and control system to support naval task force commanders engaged in crisis and combat operations.

The objective of the DDI effort has been to identify, combine and implement, in a computer-graphic form, the various decision-theoretic properties that would be appropriate to a class of decisions found in a tactical commander's contingency planning and execution phase of naval operations. Research and investigation to date has revealed several areas of apparent methodological application, and, within a tactical user sense, a number of promising decision aiding procedures have been identified for further development and evaluation.

A compact set of prototype aid specifications has been developed for application and evaluation in a workshop and testbed environment. DDI is presently refining the initial software for an interactive computer-graphic decision aid (Execution Aid) designed to assist a naval commander in planning for coping with the anti-ship missile (ASM) threat during the execution phase of task force operations. Additionally, a preliminary specification for assisting a commander in the offensive mode of battle management has been designed for computer-graphic implementation and pilot testing during a follow-on phase of research. Investigation is also continuing in an effort to find a more generalized use for the various decision analytic properties currently embodied in the prototype aids under development and evaluation as described above.

Research Tasks

The research and investigatory effort consisted of the following tasks:

- The development of evaluative criteria for determination of the conceptual value of the prototype Execution Aid as perceived by operationally experienced naval personnel in pilot testing trials.

- Pilot testing in the form of structured workshop trials in which a decision analyst and a qualified naval subject exercised the prototype Execution Aid in a simulated threat situation utilizing an interactive computer-graphic terminal.

- Modification and refinement of prototype aid software to incorporate recommended additions and features elicited from the pilot testing procedure.

- Preparation of a user's manual to support adaptation and implementation of the prototype aid in various testbed environments.

- The development of a Bayesian hierarchical inference model to exhibit the Soviet anti-ship missile (ASM) threat to form the basis for aid configuration.

- Investigation of decision aid generalization for the adaptation of potential aids to a broad class of tactical decision situations.

Research Activity

Framework for prototype execution aid trials - Although preliminary in nature, the design for the pilot test of the prototype Aid required a systematic, comprehensive and convenient form for identifying the strengths and weaknesses of the Execution Aid as evidenced by the test subject responses to Aid trials. A multi-attributed criteria matrix for Aid evaluation was investigated and discarded because of its inappropriateness to the level of testing planned, the inconvenience generated by the sophisticated matrix originally conceived as useful, and the inability to identify an existing benchmark for useful performance measurement. As a consequence, an alternative evaluative method was selected: a questionnaire that would facilitate subject response to Aid trials and that would still retain an acceptable measure of the systematic, comprehensive and convenient form desired in an evaluative tool. We feel that a multi-attribute value model may serve as a useful evaluation tool for a later test of the Execution Aid, as well as other Aids to be identified by the Project, in the more formal setting of a future testbed environment.

A second factor consistent with an informal but systematic evaluation of the prototype Aid involved the operational

situation, which had to be sufficiently realistic in order to gain user acceptance of the decision analytic methodology. Based on the expert advice of naval personnel, we identified the enemy ASM threat as one that is highly representative of hostile operational situations and well enough understood to serve both as an important illustration of the power of the Aid and as a realistic setting for the pilot test. Preliminary investigation of the ASM threat characteristics indicated that the ASM threat was both probable and sufficiently predictable to justify the need to pre-plan for its contingent occurrence. Subsequent investigation has reinforced this conclusion, and has further supported the development of a richer threat model with a high degree of user acceptance for which a "contingent aid" is worthy of operational development. A full description of the threat model is contained in Section 2.2.2 of this report.

The final element of a systematic evaluation of the prototype Aid consisted of the workshop trial itself in which a number of subjects were introduced to the Aid through the pilot test. Given the early stage of development of the Aid, we felt the most promising method of test, short of operational simulation, was the use of a workshop trial. This technique consisted of exposing a number of operational subjects to six distinct steps in the test procedure over a time period of three to four hours for each subject. The subjects were first briefed on the goals of the ODA Project, the objectives of the pilot test and evaluation, and the tactical situation facing the task force commander involved in the ONRODA scenario mission. Next, the subjects were introduced to a series of off-line (vu-graph) and on-line (computer-graphic) interactions to familiarize them with the Aid and with the decision analytic properties incorporated in it. These properties included the sensitivity features which enabled full manipulation of the Aid as the trial progressed. During the final phase of the test procedure, the subject encountered a representative sequence of threat events (indicators) in an on-line interaction with the computerized Aid. At the completion of the operational trial, the subject was queried as to his acceptance of the prototype configuration, that is, number of displays, type of displays, information content, and information logic. Finally, the subject was asked to respond to the evaluative questionnaire. The results of the pilot testing procedure were useful in defining ultimate user applications in both a training and operational sense, as well as in producing numerous suggestions for Aid refinement and software modification.

Aid generalization - Investigation into a more generalized use of the initial prototype (Execution Aid) has taken two directions during the phase of research just completed. In the first instance, we directed our efforts toward aid enhancement, specifically, the development of methods to model more than three state hypotheses and to explicitly incorporate time and risk as features of a more comprehensive aid. In the second instance, we concentrated on defining decision situations other than a task force commander's response to the ASM threat.

More than three hypotheses - With respect to examining alternatives for handling tactical situations in which more than three state hypotheses are of concern, the following methods were investigated:

- structuring the situation in a hierarchical manner and simplifying each level of the hierarchy to a three-state description;
- displaying the distances to the thresholds instead of a complete representation of the state space;
- projecting thresholds and probabilities onto planes in the state space; and
- displaying cutting-planes of the state space.

After examination of the relative merits of each approach, we tend to favor the cutting-plane method for handling situations where more than three state hypotheses must be considered. However, further investigation, including a computer-graphic implementation is necessary before a definitive recommendation can be made, particularly as it pertains to a graphical representation. A complete description of the analysis of each of the methods explored is presented in Section 3.1 of this report.

Time and risk - Investigations of time and risk factors, as incorporated features of tactical decision aids, are inconclusive at this time. Four alternatives for addressing time within the context of the air/submarine ASM threat situation were examined for their possible impact on the tactical decision of when to take or modify an action. The time alternatives addressed were:

- Time windows for executing response actions.
- Time projections of the probability bug.
- Time-dependent value functions.
- Date/Time displays for threat indicators received.

The time provisions of date/time tags on the threat indicators and the time-to-complete tags on the tables of response actions have been incorporated into the Execution Aid software. Although these concessions to the time problem are minimal, they are the only ones identified for software implementation at this time. The methods of using time-windows, time projections of probabilities, and time-dependent value functions involve estimates that appear to be virtually impossible to make in advance with sufficient accuracy to influence action selection. Aid implementation in a testbed environment may reveal further useful insights in this area of investigation.

An investigation into the stability of the action thresholds, as currently presented in the prototype Execution Aid, to the decision makers' attitude toward risk revealed a significant sensitivity. As the value tables now structured were assessed under a condition of certainty with respect to enemy intentions, the thresholds are calculated on an expected value basis which assumes a risk neutral attitude. Decision analysis literature offers several alternative methods for incorporating risk into the value assessment. However, it is not clear what method, if any, can be usefully incorporated into the prototype Aid in its present form. The methods examined for possible adaptation to the Aid included the technique of risk assuming the form of the utility function such as an exponential; specifying risk attitude in a reference gamble; and the BRLT procedure based on lotteries for different act/state combinations. The limited investigations conducted indicate a need to consider further the impact of risk aversion to the decision maker's action selection process. Furthermore, it appears that traditional methods of assessing risk may be too cumbersome when applied to the structure of a tactical decision aid, and this generates the requirement for new approaches to the problem of modeling risk attitudes.

<u>Generalized use</u> - At the request of the Scientific Officer, we undertook a second direction in our investigation of aid generalization, specifically, a search for tactical decision situations other than a task force commander's response to the ASM threat. Accordingly, the decision analytic properties of the prototype Aid were examined with the view that the key property is one of probability thresholds most applicable to situations where states are probabilistically independent of actions. The ONRODA scenario was re-examined, and the strike timing decision was identified as meeting this condition with the reservation that more than one tier of conditioning events must be considered. In addition to this generalized application, a variation of the basic properties of probability

and utility theory (in a combined aid form) were applied to the decision problem of target selection confronting the Commander, Naval Support Forces in the ONRODA Amphibious Warfare Scenario.

Strike timing generalization - A significant result of our Aid generalization investigations is the identification of the key situationally-dependent property of probability thresholds. That is, the prototype Aid is designed to monitor the tactical environment and recommend a course of action based on probability thresholds. For this reason, the Aid appears best suited to deal with operational contingencies (events of possible but uncertain occurrence) that would significantly impact mission plan and execution. Thus, it is proper to characterize the Execution Aid as a "contingency aid," and to seek out contingency situations where the state probabilities are independent of the actions, and the value of the actions can be assessed as a function of the states (that is, the specification of an action/state pair is a sufficient description of the situation to assign a value). A complete technical description and application of these features is discussed in Section 3.4 of the Report, where the strike mission timing decision bears on the overall tactical situation and where several multiple triangular display techniques are discussed. The area in which decision analysis appears most applicable at this point in our investigations is that of tactical response to contingency situations involving operational disruption by uncertain events. The generalization investigation has also indicated a wider applicability of the prototype Execution Aid to situations other than the ASM threat initially modeled. A preliminary specification for a strike mission timing aid has been completed for subsequent software development.

Tactical grid generalization - The investigation described in the preceding section was concerned with identifying a more generalized use of the properties of the prototype Execution Aid which was described in detail in our prior technical reports. In contrast, a separate investigation was conducted in which a generalized use and application of the underlying principles of probability and utility theory were implemented in computer-graphic form for aiding tactical decision making. The investigation was not limited to situations in which probability thresholds for triggering tactical responses were appropriate. Rather, we chose a situation where the task force commander, faced with multiple mission requirements, must select, on the basis of expected value, the best outcome of various target selection decisions. The tactical grid or matrix development for this case considered each of the major phases of the amphibious operation presented in the ONRODA amphibious warfare scenario, that

is, pre-assault, assault, and post-assault, in conjunction with the major mission requirements of task force defense, support of the landing force, and damage-limiting in Grey nation. Section 3.4 of the report describes in detail the model development and IBM 5100 computer-graphic implementation of the tactical grid. The investigation and demonstration indicates that decision analysis principles of probability and utility theory can in combination be used on-the-spot to formulate a useful input/output decision aid.

SUMMARY OF ACCOMPLISHMENTS AND CONCLUSIONS

Research Accomplishments

- An evaluative questionnaire, based on a list of desired decision aid characteristics, was developed for use in the pilot test. This questionnaire proved to be a convenient and efficient instrument for recording the subjects' judgments about the prototype Execution Aid.
- A range of "enemy" ASM threats was modeled in a form that could be incorporated into the Execution Aid for pilot testing. These threats included the small-scale air/submarine threat and the large-scale ASM attack system (containing air, surface, and subsurface attack elements). The modeling form consisted of a hierarchical tiering of threat activity and a list of indicators of "enemy" tactical intent, with the air/submarine model only implemented in computer-graphic software.
- A pilot test procedure, consisting of a sequence of off-line (vu-graph) and on-line (interactive computer-graphic) interactions was developed for aid evaluation. This procedure proved to be an effective way to create Aid comprehension and ease of use by the subjects tested.
- Pilot testing was conducted and the conceptual acceptance of the Execution Aid was determined. In addition, the pilot testing identified areas for software modification and refinement.
- A user's manual is being prepared to support computer-graphic implementation of the prototype Execution Aid.
- An investigation into methods of modifying the Aid to accommodate more than three state hypotheses was completed. Software specifications necessary to realize this modification were identified but have not been implemented.
- Initial investigations have been made into methods of incorporating explicit considerations of time and risk into the Aid.
- A method to display graphically more than one tier of conditioning events has been identified.

- A resource allocation aid that utilizes decision analytic principles has been developed. Prototype computer software has been developed for this aid on the portable IBM 5100 microcomputer.

- The generalized application of the prototype decision aid to situations other than reaction to the ASM threat has been established.

- A tentative matching of prototype decision aids to task force decision situations has been performed.

Conclusions

Our research, development, and testing to date has resulted in several conclusions about the acceptability and range of application of decision analysis to a Navy task force commander's mission execution decisions.

The results of the pilot testing effort indicate that the concepts involved in our decision analytic Execution Aid are acceptable to Navy task force commanders. These results lead us to conclude that the prototype Aid is now ready to undergo more thorough evaluative testing in a controlled experiment.

The investigations of the ASM attack system indicate that this threat can be adequately modeled in a Bayesian hierarchical analysis, and the Aid can usefully monitor the threat as it develops.

The investigations into the generalized use of the Aid indicate that it is applicable to a broader class of decision situations than those involving ASM threat alone. In particular, the Aid appears to be applicable to a wide range of contingencies, that is, uncertain events that might warrant a change in operational plan. The probability threshold concept appears to be especially applicable in contingency situations in which state probabilities are independent of the possible actions and value is a function of the action/state combinations. Additionally, it appears possible to extend the graphic display of the probability space to consider more than one tier of conditioning events and more than three state hypotheses within a tier.

Finally, other classes of decision aids, characterized by the requirement for on-the-spot analysis and expected value outcome of alternative decision choices, are available for development and evaluation.

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1.0 INTRODUCTION

1.1 Task Definition

1.1.1 Scope of Office of Naval Research (ONR) Operational Decision Aids (ODA) project - The objective of the ONR project for the research and development of operational decision aids has remained virtually unchanged since the program's inception. The project remains oriented toward aiding naval task force commanders in the planning and execution of naval missions using relevant man-machine technologies in an interactive computer-graphic mode as an integral part of an afloat tactical command center. The most immediate naval command system program for implementation of a proven decision aiding sub-system remains the sea-based tactical flag command center (TFCC). A prototype of this command center is currently in the concept definition phase of development by NAVELEX.

The next major ODA project undertaking will be the completion of a project testbed for prototype decision aid test and evaluation under simulated conditions of battle management. The lead unclassified testbed facility for the planned September 1976 decision aid trials is the Wharton Decision Sciences Computer Center of the University of Pennsylvania. Several classified command and control testbed facilities now in the planning stages are currently under consideration for subsequent decision aid testing where the use of classified data will be required in support of tactical simulation for the purpose of aid evaluation.

1.1.2 Decisions and Designs, Incorporated (DDI) scope and objective - As reported in DDI Technical Reports 74-2 and 75-13[1], DDI has focused research and investigation on the decision environment of naval task force commanders in order to identify, to the extent possible, classes of decision problems for which decision analytic properties can be applied as decision aiding tools. To date, a compact set of aid components to support operational planning and execution has been identified for preliminary specification and computer implementation; the current task of prototype aid development is directed toward the contingency planning and mission execution phase of naval task force operations. Prototype decision aids of this category will be evaluated later this year in the Wharton School testbed.

[1] Brown, Hoblitzell, Peterson, and Ulvila (1974) and Brown et. al. (1975).

Although a more generalized use of the types of decision aids currently identified is desired as part of the research effort, our recent direction has been to refine a single computer-graphic prototype for test and evaluation by the Navy as noted above. The investigation into adapting prototype aid characteristics to an enlarged number of decision classes/problems will continue as outlined in our current technical proposal.

1.1.3 DDI task orientation for Phase III (FY76) - As specified in DDI Technical Proposal 43-75 of 3 October 1975, the DDI task undertaking for the Phase III research effort centered on five areas of investigation:

- Development of decision aid evaluation criteria;
- Aid testing for conceptual soundness;
- Modification and refinement of Aid software and preparation of a user's manual;
- Anti-ship missile (ASM) threat modeling;
- Aid generalization (enhancement) investigations.

Subsequent tasking by the Scientific Officer added the following areas of investigation:

- Generalized use of the Aid in tactical situations other than ASM threat;
- Preliminary matching of prototype aids to tactical decision situations.

Sections 2.0 and 3.0 of this report, as well as the Appendices, provide substantive reports of our research on each of the areas cited above. As in previous investigations, the major focus of the DDI effort has been in the area of technology development, that is, a continuing search for and refinement of decision analytic tools applicable to the tactical decision environment under investigation for the purpose of identifying useful aids of an interactive computer-graphic form. There is an apparent need for evaluation of various prototype aids through trials that will stimulate user-developer interaction. It is our view that only the actual use of candidate aids will verify their full potential as decision aiding tools and encourage a satisfactory level of operational acceptance.

1.2 Research Approach

The pilot testing activity was conducted in the form of structured workshop trials in which the experimenter, a DDI analyst, and a Naval subject with operational experience exercised the prototype execution aid in a simulated threat situation utilizing an interactive computer-graphics terminal. After each pilot testing session, the subject provided his

judgments on the strengths and weaknesses of the Aid by means of a questionnaire. Since the purpose of the pilot test was to establish the conceptual acceptability of the Aid and its strengths and weaknesses as a basis for refining the computer software rather than to formally evaluate the Aid, the test was not conducted as a controlled psychological experiment.

The ASM threat element modeling was accomplished through interviews with knowledgeable Naval personnel and through a search of the relevant literature.

Mathematical analysis was used to identify possible Aid generalizations for the modeling of more than three state hypotheses, time, and risk. Workshop trials were used to evaluate the alternatives identified in each area as well as to explore the more generalized use of the Aid. These workshop trials and the applied experience of the authors were used to perform the matching task.

Finally, a major part of the effort in the contractual phase involved software programming of the Aid refinements that were identified.

2.0 PILOT TESTING FOR AID REFINEMENT[1]

Our research in Phase II of the ODA project produced an initial prototype of a computerized, interactive, graphic decision aid for the support of a naval task force commander engaged in mission execution.[2] As with most prototypes, this initial computer-graphic Aid required preliminary evaluation in order to further develop and refine the software specifications. This section of the report describes the evaluation procedure undertaken to identify modifications and refinements that would enhance user acceptance and to strengthen the Aid in preparation for a more rigorous test and evaluation in the forthcoming project testbed environment.

The preliminary Aid evaluation involved the following procedural steps:

1. Identification of a list of desired Aid characteristics.

2. Preparation of a realistic testing scenario (operational situation).

3. Performance of a pilot test.

4. Evaluation of test results for incorporation of the refinements into prototype computer software.

The following sections of this report describe the evaluation process according to the above steps: Section 2.1 describes the development of a list of desired Aid characteristics in the form of a questionnaire that is based upon multi-attribute evaluation criteria; Section 2.2 describes the development of a testing scenario based upon a model of the Soviet anti-ship missile (ASM) threat; and Section 2.3 describes the pilot testing activity and the findings obtained from the test.

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[1]Throughout this report, the authors assume that the reader is familiar with the description of the Execution Aid that is contained in Section 3 of Brown et al. (1975). While an attempt is made in this report to provide the reader with a recapitulation of the critical features of the Aid, we suggest that the serious technical reader review the material as originally presented.

[2]This aid is described in Brown et al. (1975). Hereafter, this aid will be referred to as the Execution Aid or Aid.

2.1 Development of a Framework for Eliciting Test Subjects' Responses to Aid Trials

In principle, multi-attribute evaluation criteria can be formed into a template which can then be used to evaluate a decision aid such as the Execution Aid. Such a template would involve identifying performance measures, weighting them according to their relative importance in Navy mission execution (operational) situations, and evaluating the decision aid along each criterion dimension. In pursuing the development of this scoring or evaluation technique, we concluded that the effort required to develop an accurate template was not warranted for the purposes of this preliminary evaluation. Accordingly, the following sections describe an alternative method for aid evaluation using a set of evaluative criteria transformed into a questionnaire appropriate for the pilot testing objective. Guidance is also provided to indicate the actions necessary to convert the questionnaire into a multi-attribute evaluation tool in support of a more formal test and evaluation.

2.1.1 Problem and need specification - The pilot test demanded a systematic, comprehensive and convenient vehicle for identifying areas of strength and weakness in the Execution Aid. Earlier attempts to identify any conceptual shortcomings in the Aid were carried out in a very informal manner resulting in a more or less random list of comments. Thus, a systematic, evaluative framework was required to document changes for Aid improvement. However, important performance areas were not to be overlooked. The framework needed to be comprehensive as well as systematic. Finally, the framework needed to be convenient in order to be useful for our particular pilot testing situation; that is, the nature of the pilot test required that the test subjects be responsive during the elicitation phase of the test without a great deal of prior preparation.

2.1.2 Alternative approaches - We investigated two alternative approaches in our efforts to identify a systematic, comprehensive, and convenient framework for eliciting test subjects' responses. First, we investigated the use of a template of multi-attribute evaluation criteria. Next, we investigated a questionnaire that was essentially a derivative of the more complex multi-attribute model.

Our investigation of the multi-attribute value model began by considering the notional illustration presented in Brown, et al. (1975), which is shown in Table 2-1. In this illustration, three aids, "Min," "Mod," and "Max,"[3] are evaluated for the "choice of strike plan" decision

[3]These aids are described in Section 2 of Brown, et al. (1975).

SITUATION SPECIFIC EVALUATION OF GIVEN AID CHOICE

(NOTIONAL ILLUSTRATION)

SITUATION = STRIKE CHOICE-ONRODA SCENARIO

AID COMPLEXITY	MIN	MOD	MAX	
CRITERIA	PREFORMAL RANK ORDERING	DECOMPOSED VALUATION CONDITIONED ASSESSMENT	EXTENSIVE STEP-THRU	CRITERION WEIGHT
LOGIC OF CHOICE				
CONCEPTUAL COMPLETENESS	1	2	3	10
DISAGGREGATION	1	2	3	10
SOUND PREDICTIONS	–	–	–	–
LOGICAL CONCLUSIONS	–	–	–	–
QUALITY OF INPUT				
DATA GATHERING	2	3	2	6
MANAGEMENT OF STAFF EXPERTISE	1	3	2	10
POSING MEANINGFUL QUESTIONS	3	3	1	10
SPEED OF RESPONSE				
ABILITY TO PRE-DIGEST	–	–	–	–
EASE OF ASSESSMENT	3	2	1	5
CALCULATION SPEED	3	2	1	1
TRANSPARENCY OF OUTPUT	–	–	–	–
COSTS				
COMPUTATIONAL NEEDS	3	2	1	1
PSYCHOLOGICAL DISCOMFORT	3	3	1	2
SIMPLIFIED COMMUNICATION	3	3	1	2
SITUATION DEPENDENCE OF AID	3	3	1	1
REQUIRED EXPERTISE/USER TRAINING	3	3	1	7
PRE-CHOICE PROCESSES				
MONITORING THE ENVIRONMENT	–	–	–	–
IDENTIFYING DECISIONS	–	–	–	–
OPTION GENERATION	–	–	–	–
DECISIVENESS IN ADDRESSING CHOICE	–	–	–	–
POST-CHOICE PROCESSES				
COMMUNICATION OF DECISION	1	3	1	4
JUSTIFICATION OF DECISION	1	3	1	4
EVALUATION OF DECISION QUALITY	1	3	1	3
ACCEPTABILITY OF CONCLUSIONS	1	3	2	4
ORGANIZATIONAL IMPACT				
IMPROVING INFORMATION PROCESSING	1	3	2	5
SENSITIVITY ANALYSIS	1	3	1	2
IDENTIFYING IMPORTANT INFORMATION	1	3	2	4
IMPROVING DESIGN OF C^2 SYSTEM	1	3	1	1
KEEPING CTF AT PROPER LEVEL	1	3	1	1
IMPROVING TACTICAL DOCTRINE	1	2	1	2
MANAGING SUBORDINATES	–	–	–	–
ENSURING COMMAND CONTINUITY	1	3	2	2
OVERALL VALUE	161	252	167	

Table 2-1: MULTI-ATTRIBUTE VALUE MODEL – NOTIONAL ILLUSTRATION

within the ONRODA scenario.[4] The first step in the evaluation is to indicate the relative importance of the criteria for the situation by assigning criterion weights. Next, each aid is scored with respect to each criterion. Finally, an overall value is calculated by taking a weighted sum of scores for each aid. The aid that has the highest overall value is the preferred aid for the situation. In this particular illustration, the "Mod" aid is preferred.

Upon further investigation, we concluded that this sophisticated method provided a systematic framework for eliciting subjects' responses, and that a list of some 32 criteria was indeed comprehensive. However, the multi-attribute value model did not appear to be convenient for use in the pilot test undertaken. In particular, the model was inconvenient on three counts: It included too many criteria (which were often phrased in terms that would be unfamiliar to the subjects); it required a benchmark that did not exist; and it was designed to compare aids rather than to examine the potential value of a single aid.

Based upon our test plan procedure and the overall availability of our test subjects, we estimated that one hour would be optimum for eliciting evaluative responses from the test subjects. Thus, there would not be sufficient time and prior preparation to elicit responses on all 32 value criteria. This problem was remedied by reducing the list to four primary criteria and phrasing them in a manner that would be more familiar to the subjects. The discrete criteria chosen were:

1. Timeliness of decision;
2. Quality of decision;
3. Ease of operation of the Aid;
4. Ease of understanding of the Aid.

There is no readily apparent decision aiding system in current use in the Navy that could serve as a benchmark against which to measure the Execution Aid. Thus, our investigation sought to uncover an alternative that would be both familiar to all of our subjects and sufficient to determine a scale of measurement. After searching for several alternatives, including ships with and without NTDS, various specific ships, and historical versus new ships, we concluded that a suitable scale could not be constructed in a useful way without introducing artificialities of little value.

---

[4]The ONRODA scenario, the base scenario for this project, is described in Payne and Rowney (1975).

Unless a suitable absolute scale can be constructed, the multi-attribute value model can only provide information on the relative strengths and weaknesses of alternatives. This presented an additional problem since we were attempting to evaluate a single aid. As an alternative, we considered developing and comparing three versions of the Execution Aid that had different degrees of capability:

- o A minimum version of the Aid that would simply present threat (situation) data;
- o A moderate version that would present threat data plus a probabilistic interpretation of the data;
- o A full version that would contain all of the Aid's features, that is, threat data, probabilistic interpretation of the data together with a probability threshold interpretation of the subject's values.

We felt, however, that such a comparison would not meet the objectives of the test. On the other hand, since the development of the three versions of the Aid would help to explain the Aid's features to the subjects, these versions were developed.

Reviewing the problems aforementioned in light of the purpose of the experiment--to identify software refinements--we concluded that a multi-attribute value model would hinder rather than help the evaluative effort. A questionnaire could better serve the objective of the pilot test: It would facilitate elicitation, yet remain as systematic and comprehensive as possible. Accordingly, the questionnaire was designed around the four primary criteria identified above, and its questions were phrased in terms familiar to the subjects.

2.1.3 Status and conclusions - The questionnaire was developed and used in the pilot test, and the multi-attribute value model was not developed beyond the notional stage. The questionnaire is presented as Appendix C of this report.

While our investigation concluded that the questionnaire was the appropriate framework for eliciting test subjects' responses, we feel that a multi-attribute value model might be appropriate for a later test of the Execution Aid in a more formal setting. Recall that the most serious problem with the multi-attribute value model was that we were unable to identify and construct a meaningful evaluation scale. If subsequent tests are designed to

measure the Execution Aid's performance compared with that of another aid, then the evaluation can be performed on a relative scale and the scaling problem is overcome. Our current investigation considered only one aid, so a relative scale would have been meaningless; in a future test, for instance at the project's testbed, several aids might be meaningfully compared on a relative value scale.

2.2 Modeling of Red ASM Threat Elements

In order to assess the operational acceptance of the Execution Aid by a naval user, the Aid was demonstrated in a realistic setting. In Brown *et al.* (1975), we identified the anti-ship missile (ASM) threat as one that is serious, probable, and predictable enough to support the development of the prototype Execution Aid. At that time, we also sketched the form that a "model" of this particular threat could take. However, it was recognized that a more detailed modeling effort was needed before it would be in a form acceptable to a naval commander. The following sections describe our investigations of the ASM threat: First, the air/submarine combination and, second, a full-scale combination comprised of air, surface, and sub-surface attack elements.

2.2.1 Problem and need specification - In order to properly evaluate the conceptual acceptability of the Execution Aid, and in order to extract meaningful suggestions for refinements from naval subjects, the Aid was used to address a realistic Navy problem presented to the subjects in a realistic manner. Based on the advice of expert naval personnel, we identified the ASM threat as one that is highly representative of hostile operational situations and well enough understood to serve as both an important illustration of the Aid's power and a useful setting for our pilot test. In addition, our previous investigation into the ASM threat characteristics yielded a tentative conclusion that the ASM threat was both probable and sufficiently predictable to justify the effort needed to pre-plan for its contingent occurrence in the course of naval mission prosecution.

Our initial investigation resulted in a coarse model of a single element of the ASM threat, the air/submarine combination. This model, however, was not sufficiently rich to serve as a realistic illustration of the Aid. Thus, further investigation was indicated in two areas. First, a more detailed model of the air/submarine threat was needed to serve as a setting for the pilot test. In addition, a model of the realistic, more probable threat environment was needed to serve as the basis for future tests, to demonstrate a wider application of the methodology and thus to improve its conceptual acceptability.

2.2.2 Description of threat models - Working with Navy intelligence and tactical warfare experts, we developed detailed models of two versions of the "enemy" ASM threat. The first is a model of the air/submarine strike element in which the air unit serves as a targeting platform for the submarine, the attack platform. The second is a model of a comprehensive large-scale attack system which includes air, surface, and sub-surface attack elements and is a threat of more serious concern to Navy task force commanders.

Recall the air/submarine threat described in Chapter 3 of Brown, et al. (1975). Red's hostile intent against Blue can be characterized by three states:

1. Intent to engage in routine surveillance only;

2. Intent to fully prepare to attack the Blue Task Force (stopping short of an actual attack);

3. Intent to attack the Blue Task Force.

The probabilities of these intents could be inferred from a set of indicators using a Bayesian probability updating technique. Table 2-2 shows the indicators developed in the original model and how they were used to update the probabilities of intents. An assessment is made of the prior probabilities of the intents and of the set of likelihood ratios for the indicators. The indicators are then used to update the probabilities using Bayes' theorem. As shown in Table 2-2, the probabilities of routine surveillance, full-scale preparation, and hostile action are .06, .77, and .17, based upon prior probabilities of .90, .09, and .01 and the first four indicators.[5]

The model illustrated above was the starting point for our investigation of threat, and it indicates the form that was desired for the output of the more detailed model. That is, the output of the threat model should be in the form of a list of indicators and likelihood ratios that could be used to update prior probabilities. For the indicators shown in Table 2-2, the likelihood ratios were assessed directly. However, further investigation of the threat revealed that the direct assessment technique was not workable: It was very difficult to relate the data directly to the hypotheses. Thus, we decided to use the analytic technique of Bayesian hierarchical analysis.

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[5]This Bayesian probability updating technique is explained in detail in Chapter 3 of Brown, et al. (1975).

RED INTENT / INDICATORS	LIKELIHOOD RATIOS			PROBABILITIES		
	ROUTINE SURVL	FULL-SCALE PREP	HOSTILE ACTION	ROUTINE SURVL	FULL-SCALE PREP	HOSTILE ACTION
PRIOR PROBABILITIES				0.900	0.090	0.010
1. TARGET PLATFORM DEPLOYED	10	11	11	0.891	0.098	0.011
2. TARGET-LAUNCH RENDEZVOUS	1	3	3	0.732	0.241	0.027
3. TARGETING	1	4	4	0.405	0.535	0.059
4. MISSILE SIGNAL REPORT	1	10	20	0.058	0.770	0.171
5. MISSILE LAUNCH REPORT	1	100	9999			

Table 2-2: ORIGINAL THREAT MODEL INDICATOR LIST

In Bayesian hierarchical analysis, the complex problem of relating data to hypotheses is simplified by introducing an intermediate variable and assessing the probabilities that link the data to the intermediate variable and those that link the intermediate variable to the hypotheses. If the intermediate variable is chosen properly, this procedure is much easier than attempting to assess the probabilities that link the data directly to the hypotheses.[6]

The structure of the Bayesian hierarchical model that was developed for the Red air/submarine threat is presented in Figure 2-1. In this model, a series of off-scene and on-scene activities and their associated observations that might be available to a task force commander were postulated. Then, probabilities were assessed linking the activities to the hypotheses of routine, feint, and attack, and probabilities were assessed linking the observations to the activities. For example, consider the targeting activity. We hypothesized that Red's targeting activity might occur in one of three ways, intermittently, steadily, or not at all. If Red intended no attack, it was most likely that he would not engage in any targeting, and we assessed probabilities of .10, .05, and .85 for the activities of intermittent, steady, and none (as shown in the top matrix in Figure 2-1). If Red intended feint, it was most likely that he would target in a steady fashion; thus, we assessed probabilities of .27, .68, and .05 for intermittent, steady, and none. Finally, if Red intended to attack, it was most likely that he would try to conceal his target signal by using it intermittently, and we assessed probabilities of .71, .28, and .01 for intermittent, steady, and none.

In a similar manner, the bottom matrix of Figure 2-1, linking observations to activities, was assessed. If Red actually was targeting intermittently (an activity), it was most likely that the task force commander would receive a report that Red was not targeting (an observation). Thus, we assessed probabilities of .30, 0, and .70 for the observation of intermittent, steady, and none. Further, we assessed probabilities of .10, .60, and .30 for the observation of intermittent, steady, and none given that Red's activity was steady targeting and probabilities of .04, .01, and .95 for observations of intermittent, steady, and none if Red was not targeting.

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[6]Chapter 14 of Handbook for Decision Analysis (1973) contains a technical description of Bayesian hierarchical analysis.

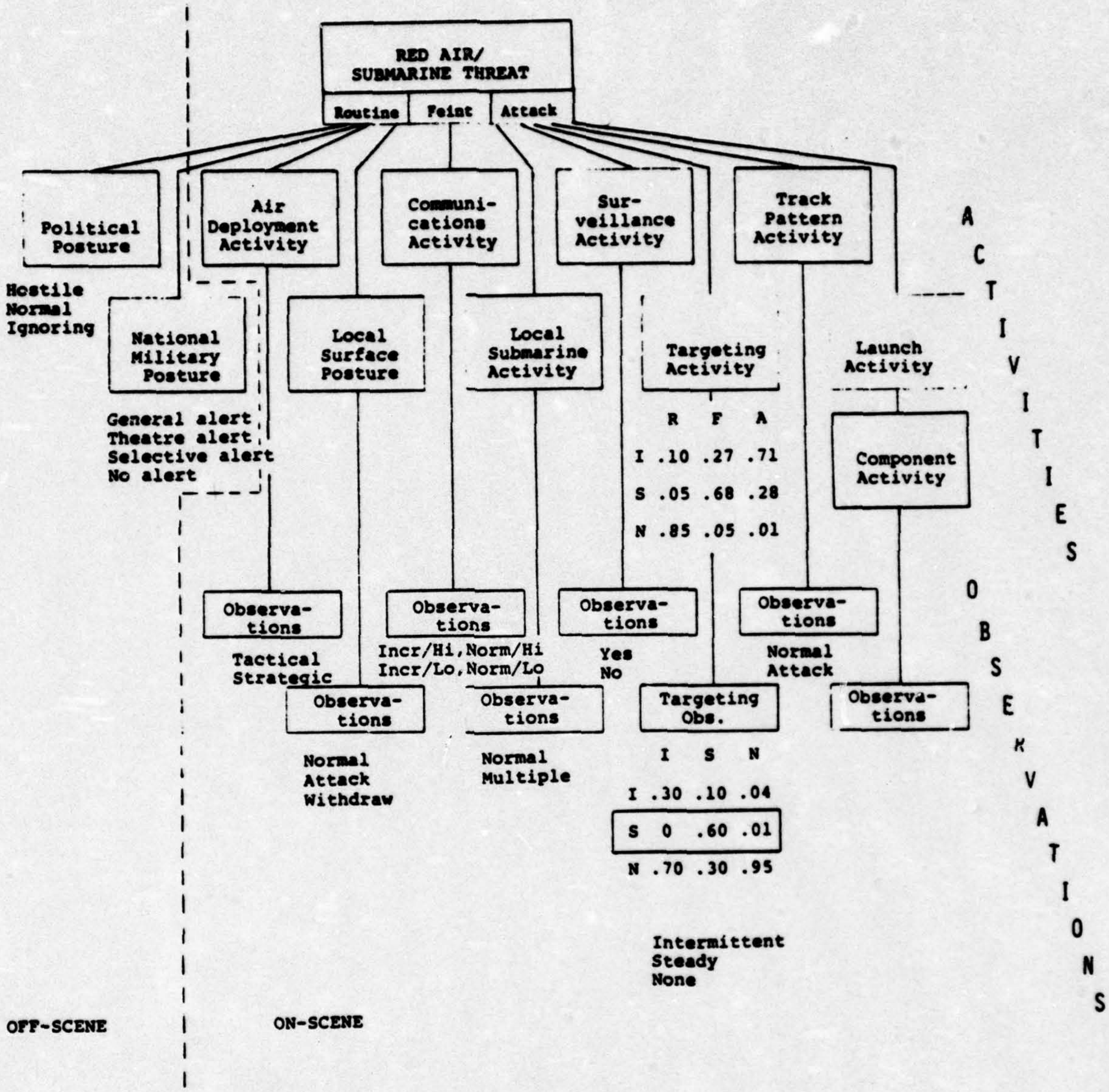

Figure 2-1

SINGLE-ELEMENT HIERARCHICAL THREAT ANALYSIS

Multiplying the lower matrix of Figure 2-1, which links the observations to the activities, by the upper matrix,[7] which links the activities to the hypotheses, yields a product matrix that relates the observations to the hypotheses. Table 2-3 shows this multiplication for the targeting example explained above. This product matrix provides output in the desired form of an indicator list relating observations to hypotheses. Table 2-4 shows the product matrices for all of the observations in the hierarchical model of the air/submarine version of the threat.

The model of the large-scale attack system is also a Bayesian hierarchical analysis. Figure 2-2 shows the form of this model. For classification reasons, the details of this model cannot be described in this report, and we are currently exploring the possibility of preparing a separate, classified document describing the model for the purpose of supporting the later test and evaluation of the Execution Aid in a classified testbed environment. However, the methodology for generating a model of the large-scale ASM threat is in itself a contributory step and can be applied in software form as a supporting decision aid module.

2.2.3 Status and conclusions - The air/submarine version of the threat has been programmed as part of the Execution Aid software, and it was used in the pilot test. The large-scale version of the threat has been modeled on paper but, because of the sensitive activity portrayed, the model is classified. A computerized implementation of this Bayesian threat model is proposed in the form of a hierarchical inference model in our current proposal. This classified model will be compatible with our evolving classified computer center facility. We are currently investigating the possibility of preparing an unclassified version that will maintain the essence of the threat model.

We feel that the Bayesian hierarchical model that has been developed for the large-scale threat is a useful model that describes the ASM threat accurately. Furthermore, we feel that the model sufficiently represents the "enemy" ASM threat as to make further modeling unnecessary at this time in order to demonstrate the usefulness and operational suitability of the Execution Aid. While there is evidence that the threat may vary somewhat with location and tactics, we feel that most of the variations are merely subsets of the comprehensive threat model and can be handled in the generic case.

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[7] See any linear algebra book, for instance Noble (1969), for an explanation of matrix multiplication.

$$
\text{Targeting Observations}
\begin{array}{l}
\\
\text{Intermittent} \\
\text{Steady} \\
\text{None}
\end{array}
\overset{\text{Targeting Activities}}{
\begin{array}{ccc}
\text{Inter.} & \text{Steady} & \text{None} \\
\end{array}}
\begin{bmatrix}
.30 & .10 & .04 \\
0 & .60 & .01 \\
.70 & .30 & .95
\end{bmatrix}
\times
\text{Targeting Activities}
\begin{array}{l}
\text{Intermittent} \\
\text{Steady} \\
\text{None}
\end{array}
\overset{\text{Threat Hypotheses}}{
\begin{array}{ccc}
\text{Routine} & \text{Feint} & \text{Attack}
\end{array}}
\begin{bmatrix}
.10 & .27 & .71 \\
.05 & .68 & .28 \\
.85 & .05 & .01
\end{bmatrix}
=
\text{Targeting Observations}
\begin{array}{l}
\text{Intermittent} \\
\text{Steady} \\
\text{None}
\end{array}
\overset{\text{Threat Hypotheses}}{
\begin{array}{ccc}
\text{Routine} & \text{Feint} & \text{Attack}
\end{array}}
\begin{bmatrix}
.07 & .15 & .24 \\
.04 & .41 & .17 \\
.89 & .44 & .59
\end{bmatrix}
$$

Table 2-3: MATRIX MULTIPLICATION

Indicators \ Red Intent		Surveil-lance	Feint	Attack
Political	- Hostile	30	84	74
	- Normal	60	14	24
	- Ignoring	10	2	2
National	- General Alert	15	20	45
	- Theatre Alert	30	52	30
	- Selective Alert	50	25	24
	- No Alert	5	3	1
Deployment	- Tactical	22	46	49
	- Strategic	78	54	51
Surface	- Normal	80	18	20
	- Attack	10	80	5
	- Withdraw	10	2	75
Comms	- Increase/High	5	33	31
	- Normal/High	12	19	22
	- Increase/Low	32	32	28
	- Normal/Low	49	16	19
Submarine	- Normal	72	50	80
	- Multiple	28	50	20
Search	- Yes	30	81	86
	- No	70	19	14
Targeting	- MW/Int.	7	15	24
	- MW/Steady	4	41	17
	- None	89	44	59
Track	- Routine	54	33	32
	- Attack	46	67	68
Beacon Test	- Yes	5	57	60
	- No	95	43	40
Guidance Radar	- Yes	5	62	65
	- No	95	38	35
Data Link	- Yes	5	67	70
	- No	95	33	30
Command Comms	- Yes	5	57	60
	- No	95	43	40
Sounds	- Yes	5	5	60
	- No	95	95	40
Intercept	- Yes	10	10	70
	- No	90	90	30

Table 2-4: PRODUCT MATRICES (AIR/SUBMARINE THREAT)

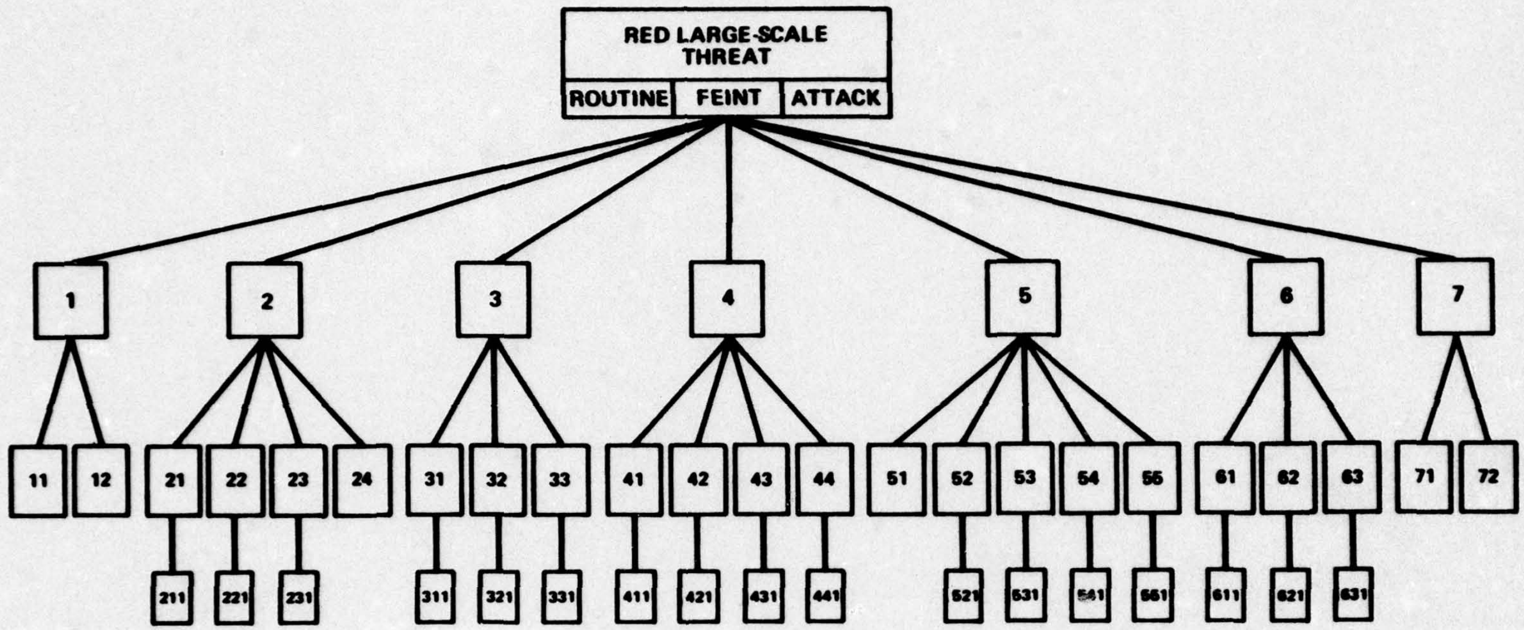

Figure 2-2

MULTIPLE-ELEMENT HIERARCHICAL THREAT ANALYSIS

2.3 Pilot Testing

The pilot testing was designed exclusively to identify areas for software modification and refinement and to establish the degree of conceptual acceptance of the Execution Aid by a representative group of naval users. Consequently, the testing activity focused on creating an evaluative environment in which the subjects could provide informed judgments on the strengths and weaknesses of the Aid rather than an experimental environment in which a subject's performance in the use of the Aid was measured under controlled conditions. The following sections describe the concept of the pilot test, its procedures, and findings.

2.3.1 Problem and need specification - As the prototype Execution Aid was conceived and partially developed during our previous contractual phase, we were uncertain about the degree of the Aid's acceptability to naval users. In addition, we recognized that, as with all new technology, the Aid would most probably require modification before it was ready to be rigorously evaluated in a testbed environment. Given the Aid's early stage of development, we felt that the most promising method of test would be a structured workshop trial in which a subject with naval experience would exercise the Aid in a simulated threat situation and provide his judgments about the Aid by responding to the questionnaire. These judgments would provide an assessment of the Aid's conceptual value as well as an indication of the Aid's perceived strengths and weaknesses as a basis for software refinement.

2.3.2 Description of pilot test procedure -

Subjects: Eight subjects were used in the workshop trials. These subjects, chosen from the following six organizations, represented a wide range of naval interests and experiences:

1. Office of the Chief of Naval Operations (OP-05)
2. Office of the Chief of Naval Operations (OP-090)
3. Office of the Chief of Naval Operations (OP-098)
4. Naval Intelligence Command (NFOIO)
5. Office of Naval Research
6. Commander in Chief Atlantic Fleet

Test Plan: The test plan was designed to provide the subject with as thorough an understanding of the Aid's function, properties, and features as possible within the time available for evaluation (typically three to four hours). This familiarization process enabled the subjects to give reasonably informed judgments in response to the questionnaire. As mentioned previously, no attempt was made to perform a controlled experiment for aid evaluation.

Six distinct steps were contained in the testing procedure. The initial two steps took the form of a briefing and served to acquaint each subject with the overall objective of the evaluation. First, the subject was introduced to the purpose of the test and the ONR Operational Decision Aids (ODA) project. In the briefing, we explained the history of the ODA project, DDI's previous and current task orientation in the project, the outline of the test that would follow, and the general form in which the subject's responses would be recorded. Second, we introduced the subject to the tactical situation facing the task force commander--an "enemy" ASM threat in the ONRODA scenario--using a sequence of graphic slides.

After this introduction, the subject was exposed to the Aid in a series of off-line (vu-graph) and on-line (computer-graphic) interactions, and his responses were recorded. In the third step of the test, the subject was exposed to the ASM threat scenario with an off-line description of Red's possible intents, possible actions that the subject might take in response to the threat, and the indicators of threat activity that would be received as the threat situation developed.[8] Next, the subject was exposed to a representative sequence of threat indicators in an on-line interaction with the computerized Aid. In the fourth step of the test, the subjects were introduced to the probabilistic component of the Aid. The Aid's probability plane was explained off-line to the subject using two examples. Then, the sequence of indicators used in step three was presented to the subjects on-line, but now a probabilistic interpretation of the data, derived from the Bayesian probability model explained in Section 2.2.2 above, was also shown. In the fifth step of the test, the subject was introduced to the value threshold component of the Aid. A series of off-line illustrations were used to explain the meaning of the Aid's value matrices and how these matrices combined to yield probability thresholds. Then, the same sequence of indicators was presented to the subject, and the probabilistic and value information was used to provide a display of the preferred decision. At this point, the subject was working with all components of the Aid, and he was encouraged to interact with the Aid, exercising its various features and decision analytic properties.

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[8]The vu-graphs used in the off-line presentations are reproduced in Appendix B of this report.

In the sixth and final step of the test, the subject was debriefed and asked to respond to the items in the questionnaire, and his judgments were recorded. The entire procedure took approximately three to four hours to complete.

2.3.3 Findings and recommendations - The subjects' evaluations and judgments expressed during the pilot test indicate that there is sufficient conceptual acceptance of the Execution Aid to justify its continued development as a tactical decision aid. The subjects' responses also indicate that the Aid may be valuable as a training device, to enable new task force commanders to become familiar with the threat and to test out alternative response actions in a simulated environment. The subjects' responses also indicate that the Aid might possibly be useful at other command levels such as the numbered fleet commander.

Additionally, numerous suggestions were made for refining the computer software to increase the Aid's usefulness and comprehension. These suggestions include:

1. A capability to recall and display an action/response option checklist automatically as the "probability bug" crosses a threshold into another decision area.

2. A provision that allows unanticipated diagnostic data to be incorporated into the model for supplementing the indicator list.

3. A way to incorporate an indication of time remaining to undertake a response option into the analysis.

4. A summary of indicators that have been received by the command center on the "action indicator" display for the commander's use.

5. A display of the expected value of the actions.

6. Automatic scrolling of the indicator list so that the indicator received last will be shown.

7. A way to handle more than three states.

The computer software changes responsive to these suggestions as well as other software changes, for example, a front-end prompt and editing feature and an expanded indicator list (which includes all of the latest air/submarine threat indicators), are described in the user's manual currently under development.

This testing activity has sufficiently identified refinements to justify a future controlled evaluative experiment. Such an experiment would attempt to measure a subject's performance in a simulated situation both with and without the Aid. Section 4.3 below recommends the prosecution of an experiment of this nature as a future task.

3.0 INVESTIGATION OF AID GENERALIZATIONS

In principle, the Execution Aid combines the methodologies of multi-attribute utility theory and Bayesian probability updating. The initial software prototype Execution Aid, however, represented a limited development of the potential power of the methodological techniques as they were implemented in a computer-graphic form. This was due, in part, to the display initially chosen, and in part to the degree of investigation possible under the previous contract phase. Thus, in order to enhance the potential of the Aid, we investigated several ways to achieve a more comprehensive Aid. Accordingly, our technical proposal outlined two areas that required further investigation, a method to model more than three state hypotheses and a method to explicitly incorporate time into the analysis.[1] In addition, our investigation under the current contract phase indicated that it may be important to incorporate the decision maker's risk attitude in the analysis. The final investigation reported below, to search for more generalized uses of the Aid in a variety of tactical situations, was undertaken at the request of the Scientific Officer. The following sections present our investigations of these areas.[2]

3.1 More Than Three State Hypotheses

Due to the geometry utilized in the current Execution Aid, only three state hypotheses can be considered in our decision modeling. That is, a two-dimensional triangular display can completely represent, at most, three state hypotheses. This fact is illustrated in Figure 3-1. The top figure shows the space of three mutually exclusive and collectively exhaustive states 1, 2, and 3. According to the rules of probability theory, all admissible probability combinations must satisfy the following conditions:

$$p(1) + p(2) + p(3) = 1.0$$
$$0.0 \leq p(1) \leq 1.0$$
$$0.0 \leq p(2) \leq 1.0$$
$$0.0 \leq p(3) \leq 1.0$$

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[1] "Proposal for Follow-on Research and Development on Decision Analysis as an Element in an Operational Decision Aiding System (Phase III)" for Office of Naval Research, 3 October 1975, pp.4-5.

[2] The following sections contain fairly detailed technical material; a reader who is unfamiliar with the concepts of the Execution Aid should review section 3 of Brown et al. (1975).

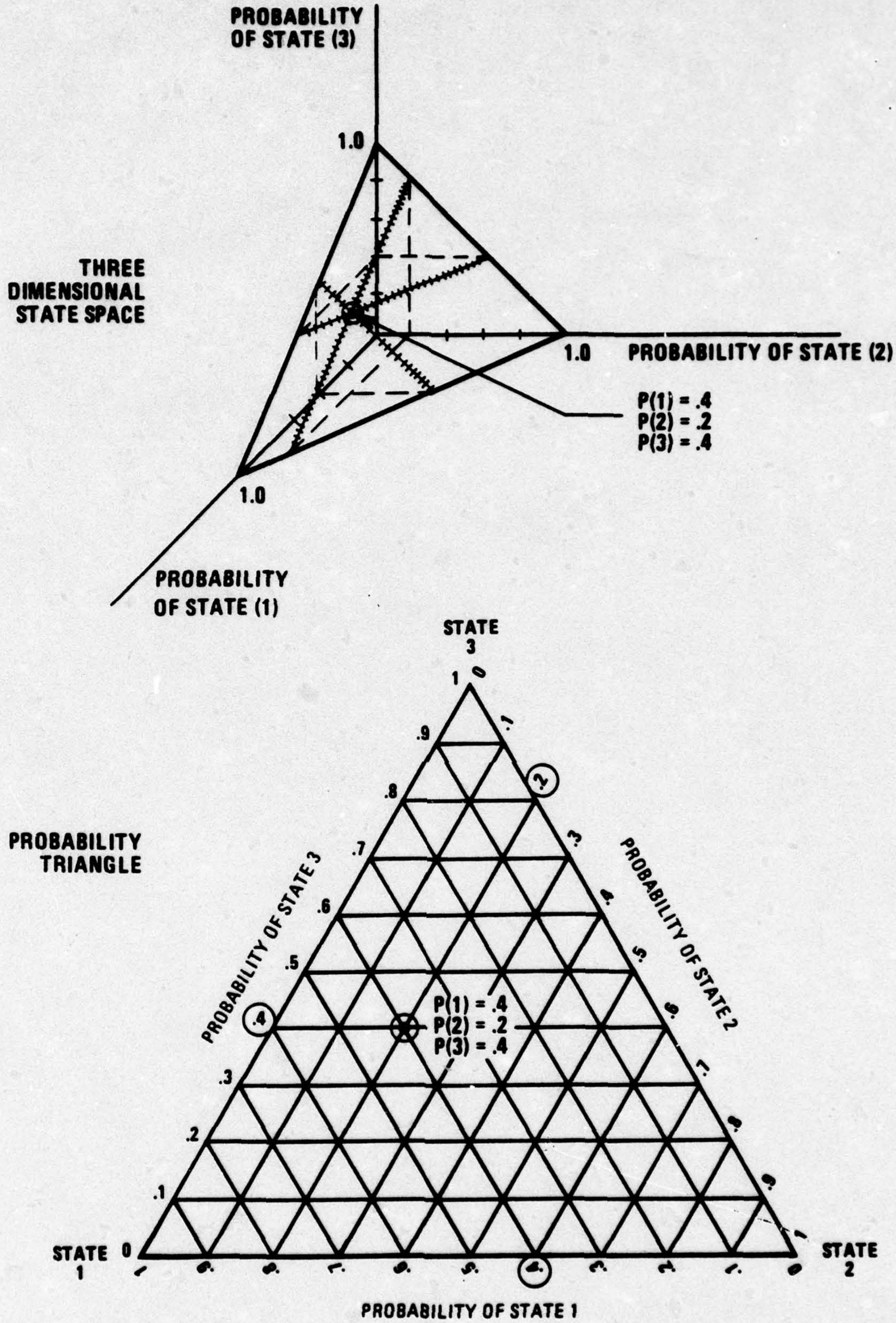

Figure 3-1

THREE-DIMENSIONAL STATE SPACE AND PROBABILITY TRIANGLE

It can be readily seen that these conditions specify the probability triangle shown at the bottom of Figure 3-1. Thus, the three-state probability space can be completely represented in two dimensions by the triangle, and the triangle is the display used in the prototype Execution Aid.

The other feature of the Aid is that of probability thresholds for actions. Figure 3-2 illustrates the decision thresholds for the actions that might be taken in response to the three states. The top of the figure shows a table of assessed values, representing the amount of loss associated with each action for each state of Red intent. Since the action with the highest expected value is always preferred, thresholds can be calculated for the actions in terms of the three probabilities. Since the thresholds are planes in the three dimensional state-space, they intersect the probability triangle in straight lines. Thus, the probability triangle can be divided into action areas, shown as counter-measure areas at the bottom of Figure 3-2. The location, or point of probability of the prevailing states, will then yield the preferred counter-measure decision. Figure 3-2 illustrates the example of a decision to take no counter-measure as the preferred action when $p(1) = .4$, $p(2) = .2$, and $p(3) = .4$.[3]

The triangular display is sufficient for those situations where only three states are important. In general, though, this may not be the case, and this characteristic has been brought to our attention by the test subjects and others. Thus, there exists a need to find a way of providing a sufficient description of a model of more than three states.[4]

Several alternatives for handling a state space with more than three hypotheses were investigated. These methods include:

- structuring the problem in a hierarchical manner in which each level of the hierarchy has three states;
- displaying the distances to the thresholds instead of a complete representation of the state space;

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[3]A fuller description of the probability and threshold displays is presented in Brown et al. (1975), pages 3-6 through 3-19.

[4]Increasing the number of states to more than three is equivalent to increasing the number of branches on the underlying probability node to more than three.

DERIVATION

COUNTER-MEASURES (ACTIONS)	RED INTENT (STATES) 1	2	3
1	0	−40	−100
2	−70	0	−20
NONE	−50	−25	0

- COUNTER-MEASURE 1 PREFERRED TO COUNTER-MEASURE 2 WHEN: $-40p_{(2)} - 100p_{(3)} > -70p_{(1)} - 20p_{(3)}$ $p_{(1)} > .6p_{(2)} + 1.1p_{(3)}$

COUNTER-MEASURE 1 PREFERRED TO NONE WHEN: $-40p_{(2)} - 100p_{(3)} > -50p_{(1)} - 25p_{(2)}$ $p_{(1)} > .3p_{(2)} + 2p_{(3)}$

COUNTER-MEASURE 2 PREFERRED TO NONE WHEN : $-70p_{(1)} - 20p_{(3)} > -50p_{(1)} - 25p_{(2)}$ $p_{(1)} > 1.25p_{(2)} - p_{(3)}$

DISPLAY

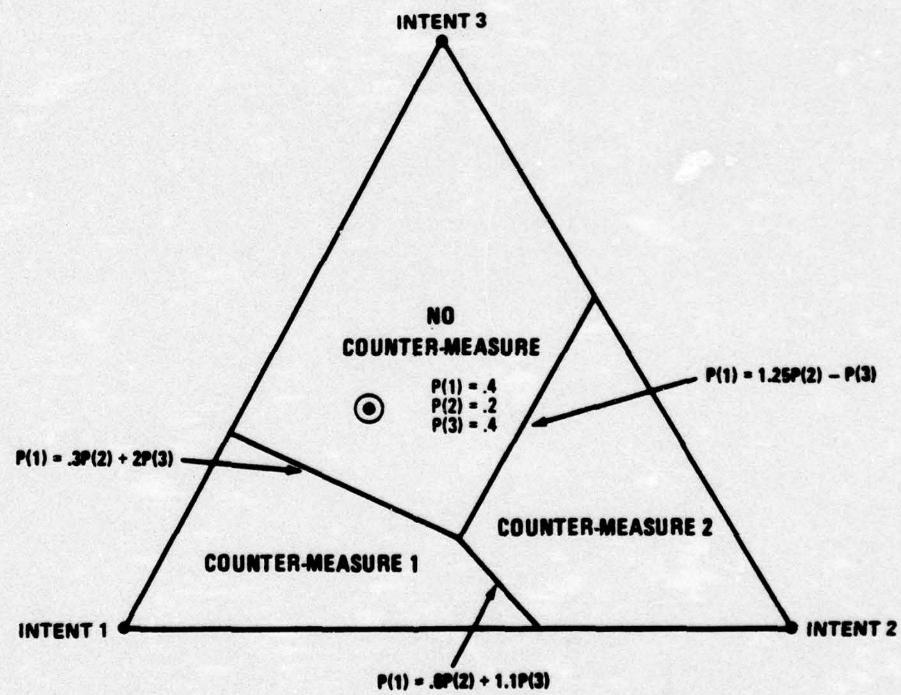


Figure 3-2

DECISION THRESHOLDS – VALUE ASSESSMENT AND DISPLAY

- projecting thresholds and probabilities onto planes in the state space; and

- displaying cutting-planes of the state space.

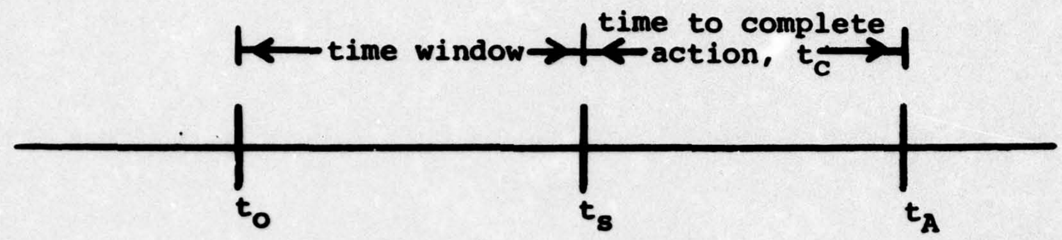
3.1.1 Status and conclusions - The investigations into graphic display modeling techniques for the treatment of more than three state hypotheses while not conclusive appear adequate for this stage of the development of decision analytic prototype decision aids. The central question remaining is the frequency and severity of situations that will generate more than three state hypotheses of concern, and the requirement for a corresponding degree of graphic sophistication required to cope with these instances. Of the various methods investigated, we cannot favor any particular technique as the most versatile with a high probability of meeting the major uncertainties of interest to a tactical commander. We believe however, that further investigation should be constrained by the outcome of the planned evaluation phase during which user interaction in a testbed environment will identify the strengths and weaknesses of prototype decision aids. (It is noted that Analytics, Incorporated, is investigating the use of nomographs for displaying tactical data for action selection.)

3.2 Explicit Consideration of Time

For many situations, it appears that when to take an action is as difficult a decision as what action to take. Thus, it is important to investigate ways in which the time factor can be considered as a feature of the Execution Aid. Our investigation to date has focused on four alternatives for addressing time, all of which were examined within the context of the air/submarine ASM threat described in Section 2.2.2 above. These alternatives were:

1. Time windows for the possible response actions.
2. Time projections of the probability bug.
3. Time-dependent value functions.
4. Time/date displays for indicators received.

3.2.1 Time windows - In the time-window method, the commander's display of the Execution Aid would provide information on the time remaining to begin each action in order to be assured of enough time to complete it. Table 3-1 shows the estimates that are needed to calculate each time window. If it takes the task force an amount of time T_C to complete an action, for example to "prepare to attack," then the action must be started T_C before t_A, the time at which the enemy attacks. Thus, at any time t_o, the time window for the "prepare to attack" action, the amount of time that remains before the commander must order the action to begin, is equal to: $t_A - T_C - t_o$.



t_o = current time

t_s = time that action is started

t_A = time of enemy attack

Table 3-1: TIME WINDOW

The current time, t_o, is trivial to determine and requires no aid other than a ship's clock. The time to complete an action, T_C, can be estimated fairly accurately, although not precisely, in advance and should be provided for in the aid. However, it appears virtually impossible to predict, in advance, the time of enemy attack, t_A, with enough accuracy to be useful in the analysis.

In the air/submarine threat, for example, it is possible for the enemy to maintain a full readiness to attack posture for 48 hours or more. Thus, an attack time that is estimated in advance and conditioned on anticipated future activities cannot be accurate to within less than 48 hours. Thus, a window cannot be estimated to within less than 48 hours, and such an estimate is of little use in the dynamic situation for which the Aid was designed. Therefore, the time-window method appears, at the present time, to be an unsatisfactory method of incorporating an explicit consideration of time into the Aid.

3.2.2 Time projections of the probability bug - In the time-projection method, the position of the probability bug is projected based upon an estimate of the timing between indicators, for example as shown in Figure 3-3. In this example, the current position is the moment that a report is received of Red withdrawing his surface ships, which yields probabilities of .75, .05, and .20 for the states routine, feint, and attack, respectively. In the probability projection method, the time between the receipt of indicators is estimated in advance. In this example, a time span of four hours is estimated for the time between the receipt of a report of Red's surface activity and the receipt of a report of his communication activity. In addition, a report of Red's submarine activity is assumed to occur four hours after the receipt of a report of his communication activity.

Based on the current location of the probability bug and the likelihoods associated with the possible communication activities, in four hours the probability bug will be at some location along the dotted line as shown in Figure 3-3. Considering the likelihoods associated with the possible submarine activities, in eight hours the probability bug will be at some location within the area bounded by the beaded line, as shown. In this illustration, the time projection of the probability bug indicates that the "routine" action will continue to be preferred in eight hours, because the eight-hour projection lies completely within the "Blue routine" action area.

Notice that the probability projection method requires a prediction, in advance, of both the ordering of the receipt of indicators and the timing between receipts. These requirements dictate an unrealistically strong assumption of the predictability of the enemy threat and the

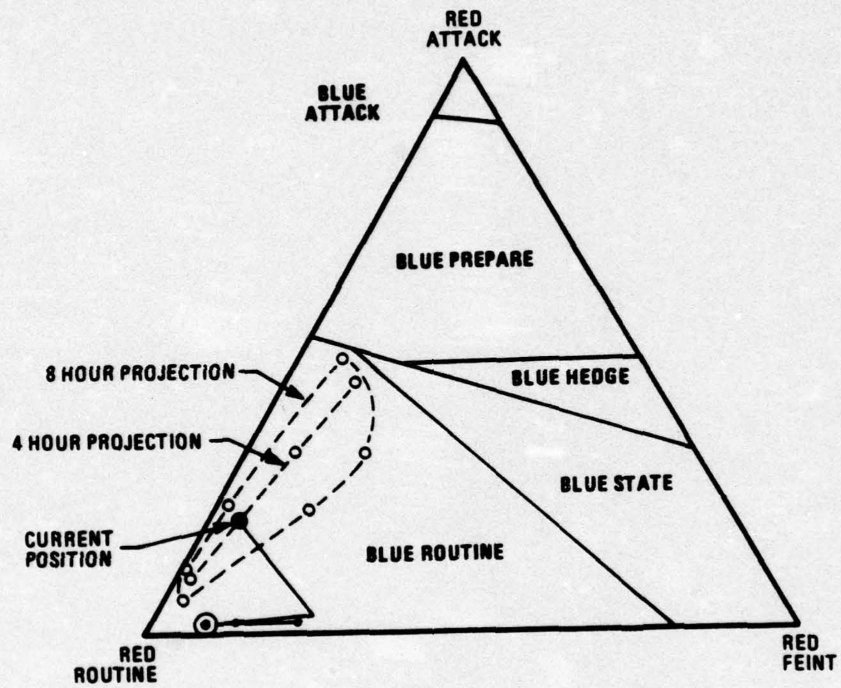


Figure 3-3
PROBABILITY BUG PROJECTIONS

ability to process information. In particular, we must assume that the enemy's activities will always occur in the same order and with the same timing between activities, that we will detect each activity at a definite time after it occurs, and that the report of an activity will always take the same amount of time to process. In addition, all of these quantities must be determined in advance.

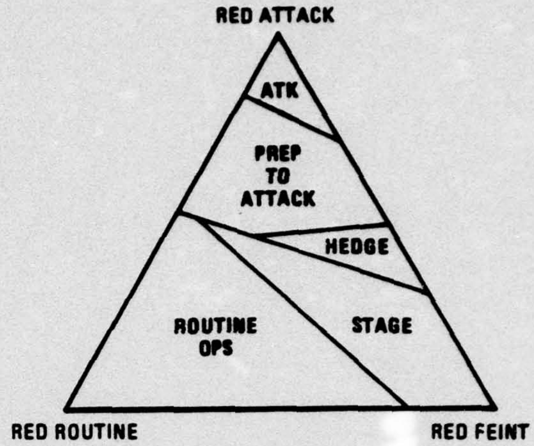
We feel that these assumptions are too unrealistic for any real event situation and that the time projection feature of the probability bug, while it is an interesting idea, is not a practical method for incorporating time into the analysis.

3.2.3 Time-dependent value functions - The time-dependent value function method requires the commander to assess several conditional value tables, which are used in the analysis, as appropriate. For example, one value table might be elicited under the condition, "if Red is going to attack, the attack will occur in 48 hours," and another value table might be elicited under the condition, "if Red is going to attack, the attack will occur in 8 hours." If it is less costly to take preparatory actions when Red's possible attack will occur in a short time period, then the probability thresholds at which such actions are indicated are lower, for instance, as shown in Figure 3-4. In the Aid's operation, the "48-hour" value table is used to determine the decision thresholds when this is assessed time until attack, and the "8-hour" value table is used to determine the thresholds when the assessed time until attack is 8 hours. Notice that this use of time-dependent value functions requires a prediction of the time at which Red will attack. Thus, this use of the time-dependent value method is unsatisfactory for the same reasons that the time-window method is, as explained in Section 3.2.1 above.

Although it appears that the time at which Red will attack cannot be predicted with precision, the minimum time to attack, determined from Red's capability to attack, can be predicted with enough accuracy to incorporate its use in the analysis. That is, a sequence of indicators could be hypothesized to predict the amount of time that would be necessary for Red to become capable of attack. However, since the enemy could attain a full readiness capability within an hour, if the launch and targeting platforms are within range, and since the enemy could hold the full readiness posture for 48 hours or more, the assessed value tables will not differ significantly over the relevant range of capability to attack (capable within one hour or less). That is, even if an estimate of capability to attack is used to predict Red's timing, the relevant time for purposes of evaluating the action alternatives is still the attack time. By introducing the capability time, the consideration of the

48 HOURS

BLUE ACTION \ RED INTENTION	ROUTINE	FEINT	ATTACK
ROUTINE OPS	−1	−7	−40
STAGE	−4	−6	−37
HEDGE	−20	−10	−27
PREPARE TO ATTACK	−43	−29	−8
DEFEND	−79	−62	−5



8 HOURS

BLUE ACTION \ RED INTENTION	ROUTINE	FEINT	ATTACK
ROUTINE OPS	−2	−12	−63
STAGE	−4	−10	−59
HEDGE	−12	−10	−40
PREPARE TO ATTACK	−28	−18	−11
DEFEND	−51	−42	−9

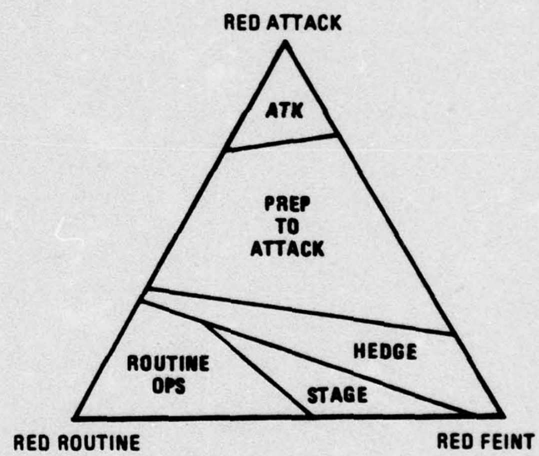


Figure 3-4
TIME-DEPENDENT VALUE FUNCTIONS

attack time has changed from a consideration of a point to a consideration of a probability distribution. That is, for purposes of determining the value of the action, the time at which the attack will occur is relevant if, as in this example, the enemy can hold a fully capable posture for 48 hours. Then the values assessed for actions given that the enemy is fully capable must implicitly consider a probability distribution for attack time spanning the period zero through 48 hours. Similarly, the values assessed for actions given that the enemy will be fully capable in one hour must implicitly consider a probability distribution for attack time spanning the period from one through 49 hours. An examination of Figure 3-5 shows that the distributions of attack times will not be significantly different and, thus, the value assessments are not expected to vary significantly. If the value assessments are not significantly different, then the effort required to make the assessments does not appear justified.

Therefore, it appears that the time-dependent value function method is unpromising for the ASM threat and other tactical situations where the enemy can attain full capability relatively quickly and hold that capability for a relatively long period of time.

3.2.4 Time/date display - The first three investigations of time appeared to hinge on predictions that are nearly impossible to usefully make in advance, and the evidence considered so far indicates that the explicit incorporation of time into the Execution Aid is an unpromising area of investigation. Still, it was felt that some modifications could be made to provide the decision-maker with improved time-related information so that he could do a better job of considering time implicitly in his decision process. The first provision involves an estimate and display of the expected time required to complete each action. (This is T_C as explained in Section 3.2.1 above.) Another provision involves identifying the time and date at which the indicators are received. Although these concessions to the time problem are minimal, they are the only ones that can be recommended at this time.

3.2.5 Status and conclusions - The minimal time provisions, date/time tags on the indicators and time-to-complete tags on the actions, have been incorporated into the Execution Aid software.

Although the explicit consideration of time initially appeared to be a promising area for aid refinement, a further investigation of some of the specific ways that time could be addressed proved to be of questionable value. In particular, the methods of using time windows,

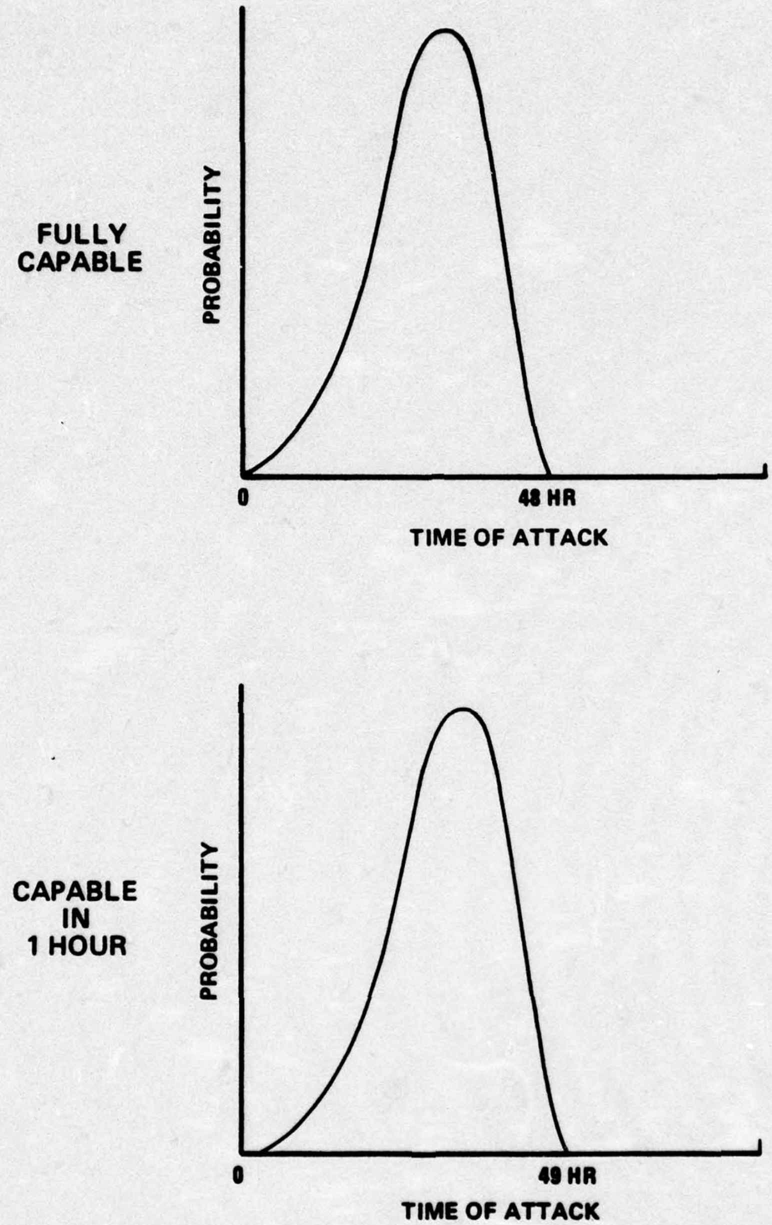


Figure 3-5

PROBABILITY DISTRIBUTIONS OF ATTACK TIME CONDITIONED ON CAPABILITY

time projections of probabilities, and time-dependent value functions involved estimates that were considered to be virtually impossible to make in advance with the accuracy required for action selection.

These investigations lead us to conclude tentatively that an explicit incorporation of time into the Execution Aid is not a promising area for aid refinement. Further investigation is necessary, however, to make a definitive statement on this issue.

3.3 Consideration of Risk[5]

An investigation into the sensitivity of the action thresholds to the decision-maker's attitude toward risk revealed that even slight risk aversion can cause significant changes in the thresholds. However, since an investigation into the incorporation of risk as a property of the Execution Aid was an extension of the proposed effort, the investigation has been limited at this time. We have, however, briefly reviewed several alternatives for addressing risk; but we have not as yet concluded which method, if any, is best. (The Naval Personnel Research and Development Center is completing an investigation of risk as a factor for incorporation in candidate decision aids.)

3.3.1 Problem and need specification - The value tables as presently developed in the Execution Aid were assessed under the condition of certainty; that is, the value for an action was assessed assuming that Red's intent is known for certain. Thus, the thresholds are calculated on an expected value basis, which assumes that the decision-maker is "risk-neutral." Since decision-makers do not always exhibit this attitude toward risk, but rather an attitude which is risk-seeking or risk-averse, the sensitivity of the thresholds to the assumption of risk neutrality deserves further investigation.

For purposes of checking the sensitivity of the thresholds to risk, an experimental function of the form $u(x) = \frac{c}{r}(1 - e^{-rx})$, where r is the coefficient of risk aversion and c is a scaling constant[6], was used to calculate

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[5] Some of the material in this section assumes that the reader has a technical knowledge of the concepts of risk attitude and utility theory. Introductory discussions of these topics appear in Chapters 4 and 18 of Brown, Kahr, and Peterson (1974); Chapter 4 of Raiffa (1968); Chapter 5 of Schlaifer (1969); and Chapter 5 of Handbook for Decision Analysis (1973).

[6] This is a positive, linear transform of the function of constant risk aversion described on page 156 of Schlaifer (1971).

the utility for the values, u(x). This function was chosen because it exhibits a constant aversion to risk, which is a reasonable approximation of a decision maker's actual risk aversion in many cases, and because it facilitated calculations.[7] For the purpose of checking the sensitivity of the thresholds to risk, the curve $u(x) = 303\ (1 - e^{-x/250})$ was chosen because it does not differ significantly from a risk neutral curve, as shown in Figure 3-6. If the analysis is insensitive to risk, then the thresholds derived by using this utility curve should be virtually the same as the thresholds derived by using the risk neutral, expected value curve.

The example in Figure 3-7 shows, however, that this is not the case.[8] Introducing risk into the analysis causes the areas for actions "H" and "R" to collapse to about 15% and 60% of their riskless sizes, respectively, while the areas for actions "P" and "S" increase by about 25% and 85% respectively. Clearly, such changes are significant, indicating that it is worthwhile to investigate methods of incorporating risk into the analysis to assure maximum usefulness in the Aid's configuration.

3.3.2 Alternative approaches - Decision analysis literature offers several alternative methods for incorporating risk into the analysis. However, it is not clear what method, if any, can be usefully incorporated into the prototype Execution Aid in its present use and form.

One method for handling risk involves assuming the form of the utility function, such as an exponential, and then eliciting the necessary parameters from the decision-maker. For instance, in the case of the exponential utility function described in the previous section, the value of the parameter r would be elicited from the decision maker. This technique is available in the computer program described in Zamora and Leaf (1974). This method, however, requires the decision-maker to comprehend both the implication of the functional form chosen and the curve that would result from using any particular value of the parameters. These assumptions are not easily met in practice by naval personnel without extensive training, so this method would probably not be a useful feature of the Execution Aid.

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[7] Pratt (1964) contains a full discussion of the measure of risk aversion and examples of functions exhibiting constant, increasing, decreasing, and constraint-proportional risk aversion.

[8] The expected value (risk neutral) results of this example are approximately the same as those obtained from our model of the air/submarine ASM threat.

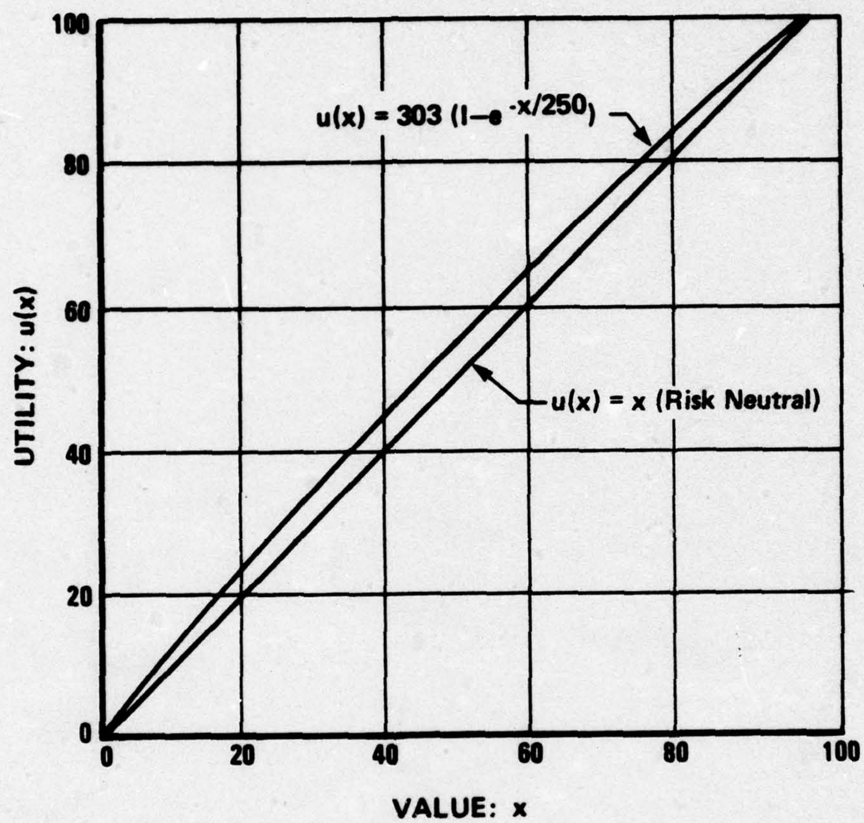
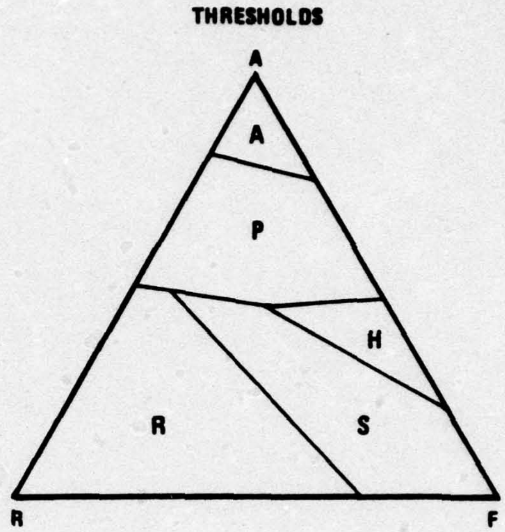


Figure 3-6
RISK AVERSE AND RISK NEUTRAL UTILITY CURVES

RISK NEUTRAL $u(x) = x$

UTILITY TABLE

RED INTENT / BLUE ACTION	R	F	A
R	100	91	0
S	97	92	5
H	85	88	13
P	67	73	33
A	34	45	35



SLIGHTLY RISK AVERSE $u(x) = 303\,(1-e^{-x1250})$

UTILITY TABLE

RED INTENT / BLUE ACTION	R	F	A
R	100	89	0
S	96	90	4
H	82	86	11
P	62	69	29
A	30	40	31

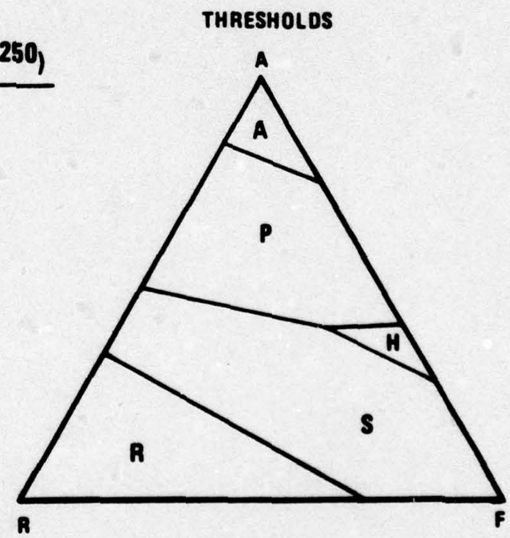


Figure 3-7

THRESHOLDS CALCULATED FROM UTILITY CURVES

Another method to handle risk assumes the functional form of the utility curve, but does not require the decision-maker to enter parameters. Instead, he specifies his risk attitude in a reference gamble. A curve, which exhibits the specified form, is then fit to the information contained in the reference gamble. This reference-gamble method, available in the computer program described in Schlaifer (1971), does not require the decision-maker to know what curve will result from a particular choice of the parameters; but it still requires him to know the implications of the functional form chosen. Thus, the reference-gamble approach may be too demanding of the decision-maker to be routinely useful in the Execution Aid.

As another alternative, the utility table could be evaluated directly by eliciting values based upon lotteries for different act/state combinations using a method such as the π-BRLT procedure described in Chapter 4 of Raiffa (1968). Determining a utility table directly, however, is probably too laborious and time-consuming (since many lotteries must be considered) to be useful in the Execution Aid's implementation.

3.3.3 Conclusions and findings - Our limited investigations to date indicate that is is important to find a way in which the decision-maker's attitude toward risk can be usefully incorporated into the Execution Aid. Furthermore, it appears that traditional methods of addressing risk may be so difficult to apply in practice that they reduce rather than enhance the usefulness of the Aid by making it too cumbersome to operate. Thus, new approaches to the problem of modeling risk attitudes may need to be developed, and this area is recommended for future investigation.

3.4 Generalized Use

At the direction of the Scientific Officer, we investigated the generalized use of the prototype Execution Aid in situations other than a task force's response to the ASM threat. This investigation has taken two directions. First, the properties of the Aid were examined with the view that the key property of this aid is one of probability thresholds and that this property is most applicable in situations where states are probabilistically independent of actions. Based on this, the ONRODA scenario was re-examined, and the strike timing decision was identified as one that meets this condition with the reservation that more than one tier of conditioning events must be considered. Section 3.4.1 below describes the application of the Execution Aid to the strike

timing decision. Second, in addition to this generalized application, the basic properties of decision analysis (that is, probability and utility theory) were applied in a different manner to the problem of target selection in the "Amphibious Warfare Scenario" (Rowney [1975]). This application is explained in section 3.4.2 below.

3.4.1 Execution aid-contingent mode - The main finding from the investigation of the generalized use of the Execution Aid was an identification of the key situationally dependent property of the Aid, that of probability thresholds. That is, the Aid is designed to monitor the environment and recommend a course of action based upon probability thresholds. For this reason, the Aid seems most suited to addressing operational contingencies, events of possible but uncertain occurrence, that would be disruptive enough to cause a change in the mission plan. In addition, it appears that the Aid is most useful when the problem can be structured so that:

1. The state probabilities are independent of the actions; and

2. The value of the actions can be assessed as a function of the states (that is, the specification of an action/state pair is a sufficient description of the situation to assign a value).

For such problems it is proper to consider the appropriateness of the actions in terms of the probabilities of the states by establishing probability thresholds. Thus, it is proper to think of the Execution Aid as a Contingecy Aid and to seek out contingencies that exhibit the two features described above.

One such contingency that we feel meets the conditions of probabilistic independence of actions and states and functional dependence of an action's value on the state is that of strike mission timing, whether to change the planned time of a strike. This decision situation has been examined within the context of the air strike mission in the ONRODA scenario and is illustrated below.

In the operational situation presented, an early morning air strike is planned against the airfield on ONRODA island. However, when planning for this mission, the task force commander (CTF) recognized the possibility that the mission may, at the last minute, have to be delayed due to unfavorable weather, the state of readiness of his own forces, the state of readiness of the enemy, or some combination of these factors. In the face of these uncertainties,

delay of the initial strike for either an hour or a day was considered. A decision tree structure of this decision problem is shown in Figure 3-8. Here, the action node is followed by three tiers of conditioning events, one each for the states of weather, enemy readiness, and own-force readiness. Each tier of events is characterized by three state possibilities. Weather can be classified as good, marginal, or bad; enemy readiness can be classified as unprepared, partially prepared, or completely prepared; and own-force readiness can be classified as completely prepared, partially prepared, or unprepared. Thus, there are twenty-seven combinations of event states that must be considered in connection with each action.

An evaluation of this decision situation indicated that the strike-timing problem could be adequately modeled by treating each event as probabilistically independent of the actions and of the other events, and by assessing values based directly on the action/state combinations. Thus, this problem satisfied the contingent conditions that are necessary to apply the Execution Aid.

However, it was recognized that the display of the Execution Aid, a single probability triangle, could handle only one tier of conditioning events and that the strike-timing decision problem required three tiers of conditioning events. A method had to be found to incorporate the additional tiers. Based upon our earlier investigation of the generalization to consider more than three states within a single tier (described in Appendix D), we recognized that a display of multiple triangles, in the cutting-plane method, offered an appealing and manageable display. Investigation revealed that a multiple-triangle display could be developed for several conditioning tiers in a manner analogous to the cutting-plane method used for more than three states within a tier.

Figure 3-9 shows the multiple-triangle graphic display for the strike-timing decision. Given the initial probability assessments for the three state variables, the preferred action is to proceed with the strike as planned, with no delay. The display shows that at the initial probability assessment, this decision is most sensitive to changes in the weather; that is, the weather probability bug is close to the decision threshold to delay an hour. The decision is insensitive to the state of enemy readiness (at the assessed state of own-force readiness and weather), and no change in the assessment of the enemy's readiness would be reason enough to delay the strike. Finally, the decision is somewhat sensitive to the state of own-force readiness, where a significant change in this assessment would be reason enough to delay the strike.

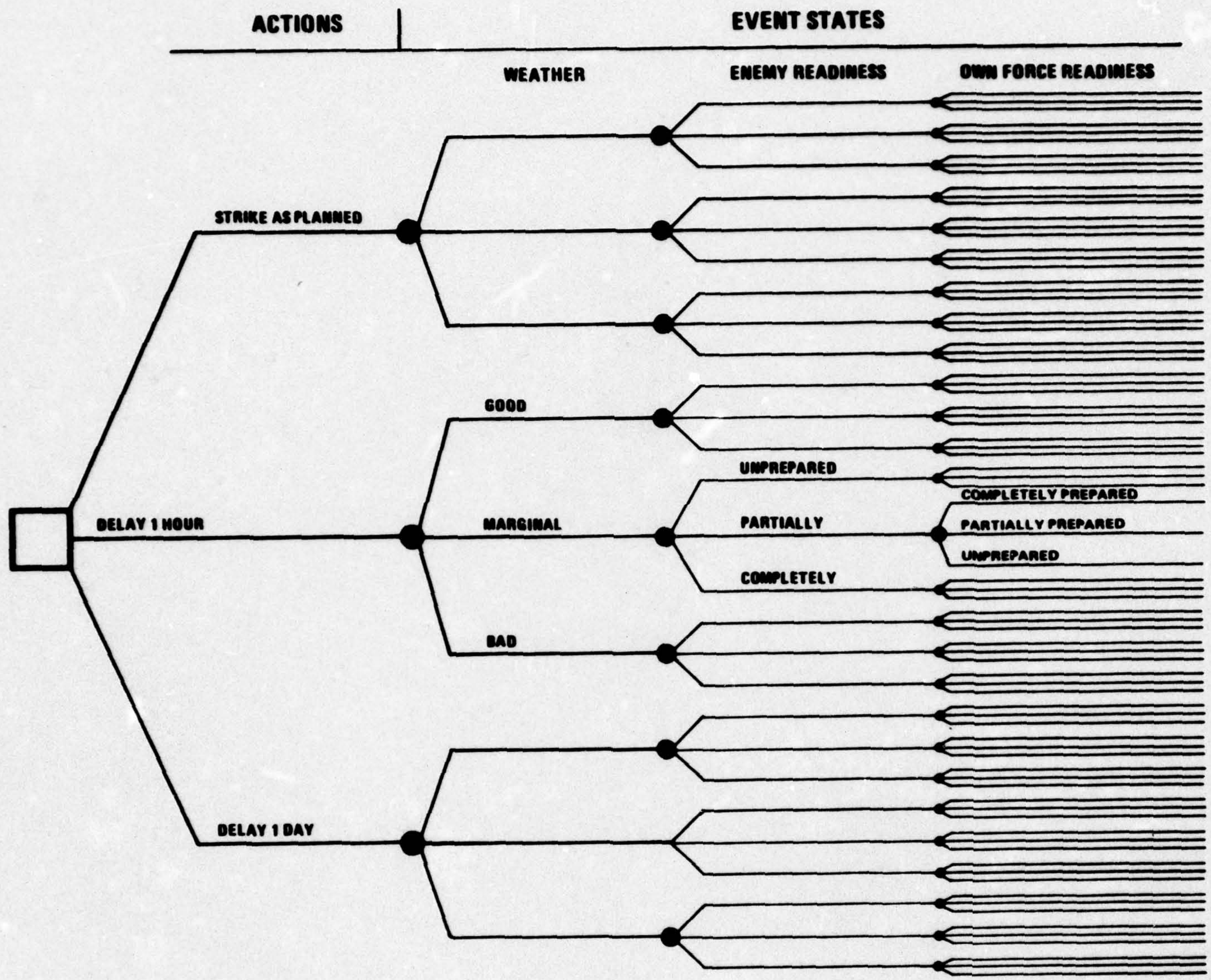


Figure 3-8

STRIKE TIMING DECISION – TREE STRUCTURE

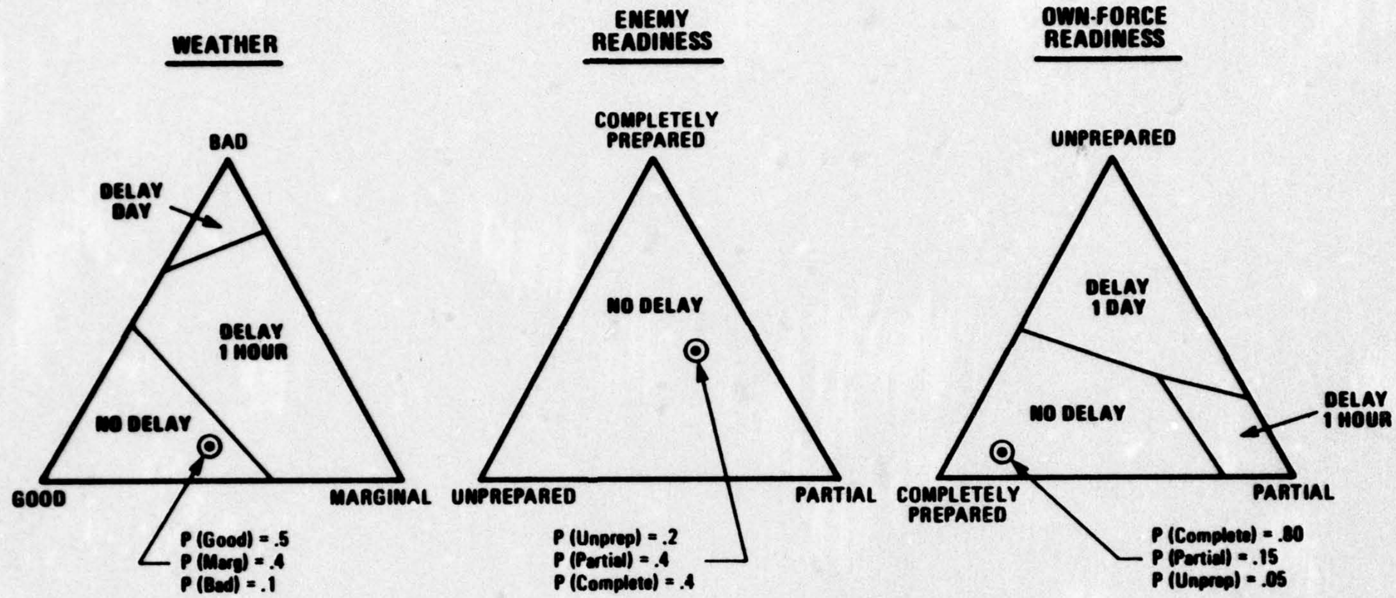


Figure 3-9

STRIKE TIMING DECISION – GRAPHIC DISPLAY (INITIAL PROBABILITY ASSESSMENT)

The decision thresholds were determined from the assessed value tables shown in Table 3-2. In this case, the values of the action/weather combinations were assessed to be independent of the other events. However, the own-force readiness and enemy readiness states needed to be considered in combination for valuation purposes. The importance weights show that the readiness of forces has twice as much effect on the strike-timing decision as the weather does. This form of the value table is satisfactory for eliciting the assessments, but it does not directly provide the information needed to calculate the thresholds. Table 3-3 shows a convenient format for calculating the decision thresholds. This format is analogous to that used in the cutting-plane method and illustrated in Figures D-21 and D-22. For the weather thresholds shown in the top of Table 3-3, first an importance-weighted table of values is obtained by multiplying each entry of the assessed value table for weather (from Table 3-2) by its importance weight, .33. Next, the value of each action must be adjusted to account for the probabilities of enemy and own-force readiness. This adjustment is calculated by weighting the assessments in the enemy and own-force readiness value tables by both importance and probability and summing across rows. For example, the adjustment, due to enemy and own-force readiness, for the action "delay 1 day" is calculated as follows:

OWN FORCE	ENEMY	ASSESSED VALUE	x	IMPORTANCE	x	PROBABILITY	=	PRODUCT
C	C	-10		.67		.8 x .4		-2.14
C	P	-30		.67		.8 x .4		-6.43
C	P	-15		.67		.8 x .2		-1.61
P	X	0		.67		.15 x .4		0
P	P	-5		.67		.15 x .4		-0.20
P	N	-25		.67		.15 x .2		-0.50
N	C	0		.67		.05 x .4		0
N	P	0		.67		.05 x .4		0
N	N	0		.67		.05 x .2		0
						TOTAL		$-10.88 \cong -11$

This adjustment, -11, is added to each entry in the "day delay" row of the weather value table, and the other adjustments are calculated in a similar manner to obtain the table from which the weather probability thresholds can be calculated, shown on the right of Table 3-3.

The value tables for thresholds on enemy readiness and own-force readiness are calculated in a manner slightly different from that used for the thresholds on

WEATHER / ACTIONS	GOOD	MARG	BAD	IMPORTANCE WEIGHTS
NO DELAY	0	-35	-100	
HOUR DELAY	-50	0	-40	.33
DAY DELAY	-80	-70	0	

FORCE READINESS / ACTIONS	COMPLETELY READY			PARTIALLY READY			NOT READY			OWN-FORCE READINESS
	C	P	N	C	P	N	C	P	N	ENEMY READINESS
NO DELAY	0	0	0	-40	0	0	-100	-80	0	
HOUR DELAY	-5	-5	-1	-25	-2	-2	-90	-70	0	.67
DAY DELAY	-10	-30	-15	0	-5	-25	0	0	0	

Table 3-2: STRIKE TIMING DECISION – ASSESSED VALUE TABLE

WEIGHTED VALUE + **EXPECTED WEIGHTED VALUE** **= AGGREGATED EXPECTED VALUE**

WEATHER

	Weather		
	Good	Marg	Bad
NO DELAY	0	−12	−33
HOUR DELAY	−17	0	−13
DAY DELAY	−27	−23	0

From Enemy & Own-Force
−4
+ −6
−11

	Weather		
Actions	Good	Marg	Bad
NO DELAY	−4	−16	−37
HOUR DELAY	−23	−6	−19
DAY DELAY	−38	−34	−11

ENEMY READINESS

	Enemy Readiness		
Actions	Comp.	Part.	Not
NO DELAY	−7	−3	0
HOUR DELAY	−8	−5	−1
DAY DELAY	−6	−16	−11

From Weather
−8
+ −10
−22

	Enemy Readiness		
Actions	Comp.	Part.	Not
NO DELAY	−17	−13	−10
HOUR DELAY	−15	−12	−8
DAY DELAY	−28	−38	−33

OWN-FORCE READINESS

	Own Force Readiness		
Actions	Comp.	Part.	Not
NO DELAY	0	−11	−48
HOUR DELAY	−3	−8	−44
DAY DELAY	−13	−5	0

From Weather
−8
+ −10
−22

	Own Force Readiness		
Actions	Comp.	Part.	Not
NO DELAY	−10	−21	−58
HOUR DELAY	−10	−15	−51
DAY DELAY	−35	−27	−22

Table 3-3: STRIKE TIMING DECISION – VALUE TABLES FOR THRESHOLD CALCULATIONS

weather. The difference is that the initial value table for enemy readiness must consider the probability distribution over states of own-force readiness and vice versa. For example, the value for the action/state combination "No Delay/Enemy Completely Ready" on the left of Table 3-3 has a value of -7 calculated as follows using data from Figures 3-9 and Table 3-2:

STATE OF ENEMY READINESS	STATE OF OWN FORCE READINESS	ASSESSED VALUE	x	IMPORTANCE	x	PROBABILITY OF OWN FORCE READINESS STATE	=	PRODUCT
C	C	0		.67		.80		0
C	P	-40		.67		.15		-4
C	N	-100		.67		.05		-3
						TOTAL		-7

The adjustment for each is now based upon the weather probability, but it is calculated in the same manner as the adjustment to the weather value table. For example, the adjustment, due to weather, for the action "delay 1 day" is calculated as follows:

STATE OF WEATHER	ASSESSED VALUE	x	IMPORTANCE	x	PROBABILITY	=	PRODUCT
Good	-80		.33		.5		-13
Marginal	-70		.33		.4		-9
Bad	0		.33		.1		0
					TOTAL		-22

The value tables that contain the necessary information for calculating thresholds are shown on the right of Table 3-3.

The effect of changing the probabilities of the states of weather is shown in Figure 3-10. Increasing the probability of marginal weather enough for the "delay 1 hour" decision to be preferred changes the position of the probability bug in the weather triangle and the positions of the thresholds in the enemy and own-force readiness triangles. This change in weather causes the entire enemy readiness triangle to change from favoring "no delay" to favoring "delay 1 hour." In the own-force readiness triangle, the action space for "delay 1 hour" was greatly increased while the action space for "delay 1 day" was decreased; and the action space for "no delay" was eliminated (the previous thresholds are shown as dotted lines in

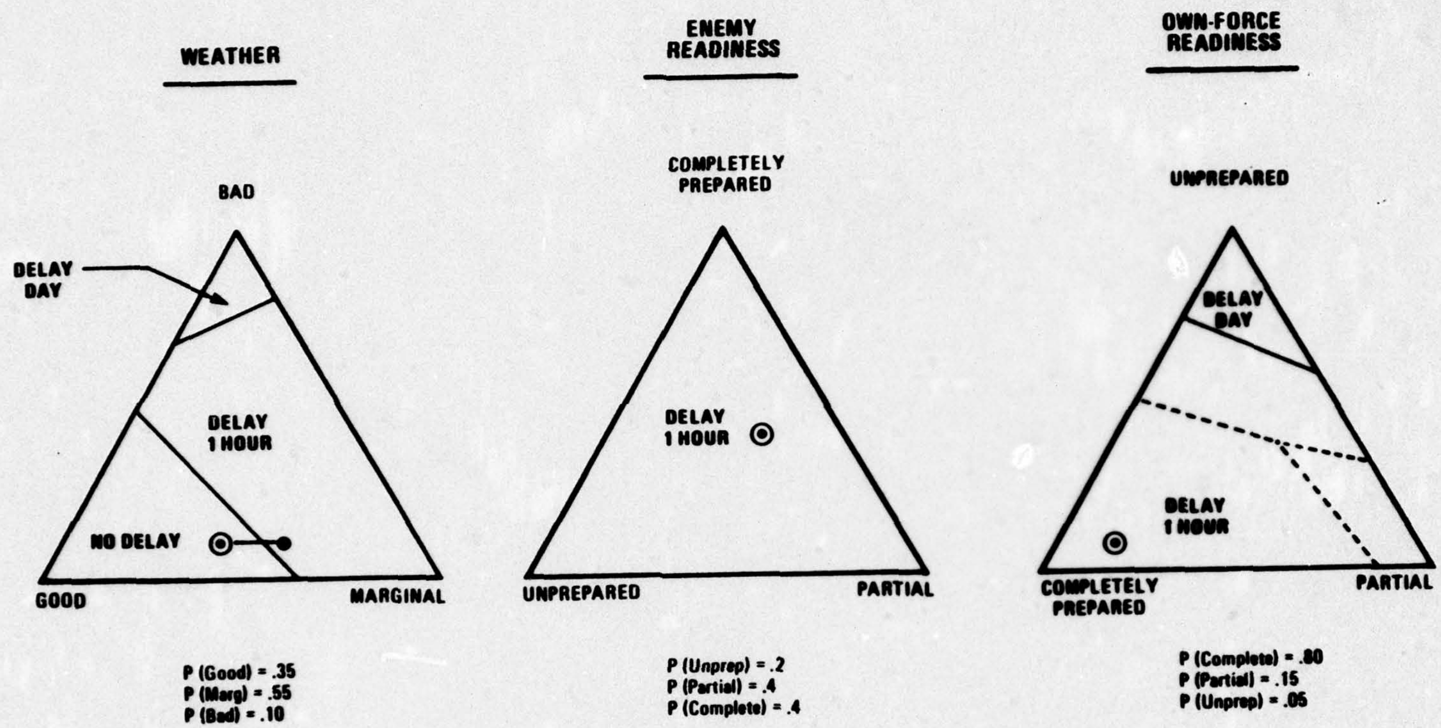


Figure 3-10

STRIKE TIMING DECISION –
REVISED WEATHER PROBABILITIES

Figure 3-10). Therefore, at this new assessment of weather, no change in enemy or own-force readiness could cause the "no delay" action to be favored, and only a large change in the assessed state of own-force readiness could cause the "delay 1 hour" action to be favored.

The value tables that were used to calculate these new thresholds are shown in Table 3-4. Since the probabilities of enemy and own-force readiness remained constant, the only changes in the threshold tables are in the adjustments due to weather, which are added to the rows of the enemy-readiness value table and the own-force-readiness value table.

This formulation and display of the strike-timing decision appears to be a satisfactory way to model the decision problem. However, our investigation also uncovered an alternative formulation, one that combines the features of more than one conditioning tier (described above) and more than three states within a tier (described in section 3.1). This formulation appears to provide a more direct elicitation of value, and, for this reason, it may be a preferable formulation of the problem.

Figure 3-11 shows the decision tree structure for this alternative formulation of the problem. The actions are the same and the state of weather are the same. However, the states of enemy and own force readiness are different. Now, the <u>net</u> readiness of the enemy (Red) and own (Blue) forces is modelled. This net readiness is characterized in terms of five states:

1. Blue much greater than Red,
2. Blue greater than Red,
3. Blue equal to Red,
4. Blue less than Red,
5. Blue much less than Red.

Figure 3-12 presents the graphic display of the model using both the multiple-triangle method described above, and the cutting-plane method (described in section 3.1.4) for the "force readiness" event tier. The top set of triangles shows the model for one assessment of probabilities; the middle set of triangles shows the changes caused by changing the weather probabilities; and the bottom set of triangles shows the changes caused by changing the force readiness probabilities. Table 3-5 shows the assessed value tables that were used to derive the thresholds.[9]

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[9] The numbers in this illustration are unrelated to those in the previous illustration.

WEIGHTED VALUE + EXPECTED WEIGHTED VALUE = AGGREGATED EXPECTED VALUE

WEATHER

	Weather					Weather		
	Good	Marg	Bad	From Enemy & Own-Force	Actions	Good	Marg	Bad
NO DELAY	0	−12	−33	−4	NO DELAY	−4	−16	−37
HOUR DELAY	−17	0	−13	+ −6	HOUR DELAY	−23	−6	−19
DAY DELAY	−27	−23	0	−11	DAY DELAY	−38	−34	−11

ENEMY READINESS

	Enemy Readiness					Enemy Readiness		
Actions	Comp.	Part.	Not	From Weather	Actions	Comp.	Part.	Not
NO DELAY	−7	−3	0	−10	NO DELAY	−17	−13	−10
HOUR DELAY	−8	−5	−1	+ −7	HOUR DELAY	−15	−12	−8
DAY DELAY	−6	−16	−11	−22	DAY DELAY	−28	−38	−33

OWN-FORCE READINESS

	Own Force Readiness					Own Force Readiness		
Actions	Comp.	Part.	Not	From Weather	Actions	Comp.	Part.	Not
NO DELAY	0	−11	−48	−10	NO DELAY	−10	−21	−58
HOUR DELAY	−3	−8	−44	+ −7	HOUR DELAY	−10	−15	−51
DAY DELAY	−13	−5	0	−22	DAY DELAY	−35	−27	−22

Table 3-4: STRIKE TIMING DECISION – REVISED VALUE TABLES FOR THRESHOLD CALCULATIONS

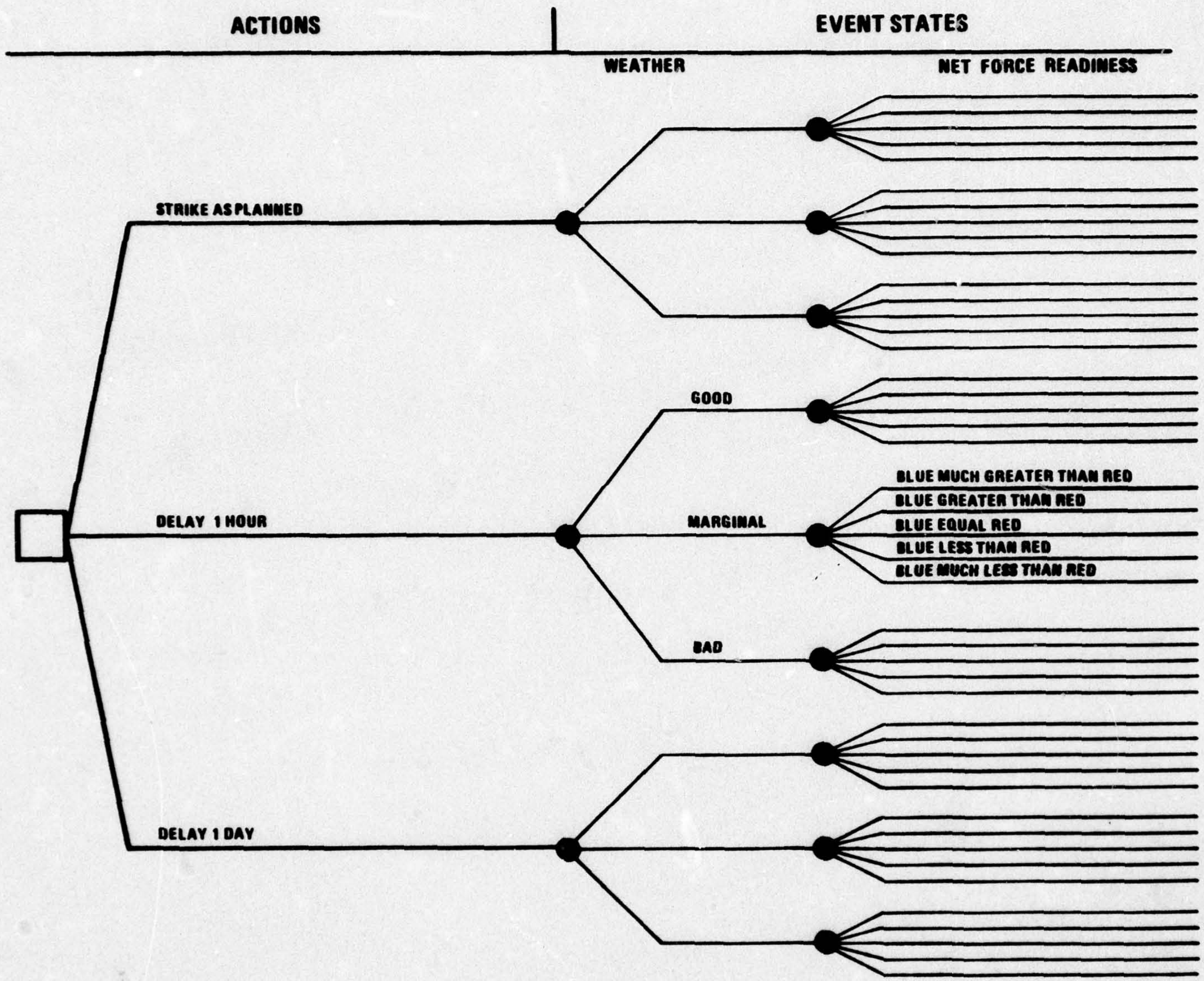

Figure 3-11

ALTERNATIVE STRIKE TIMING MODEL — TREE STRUCTURE

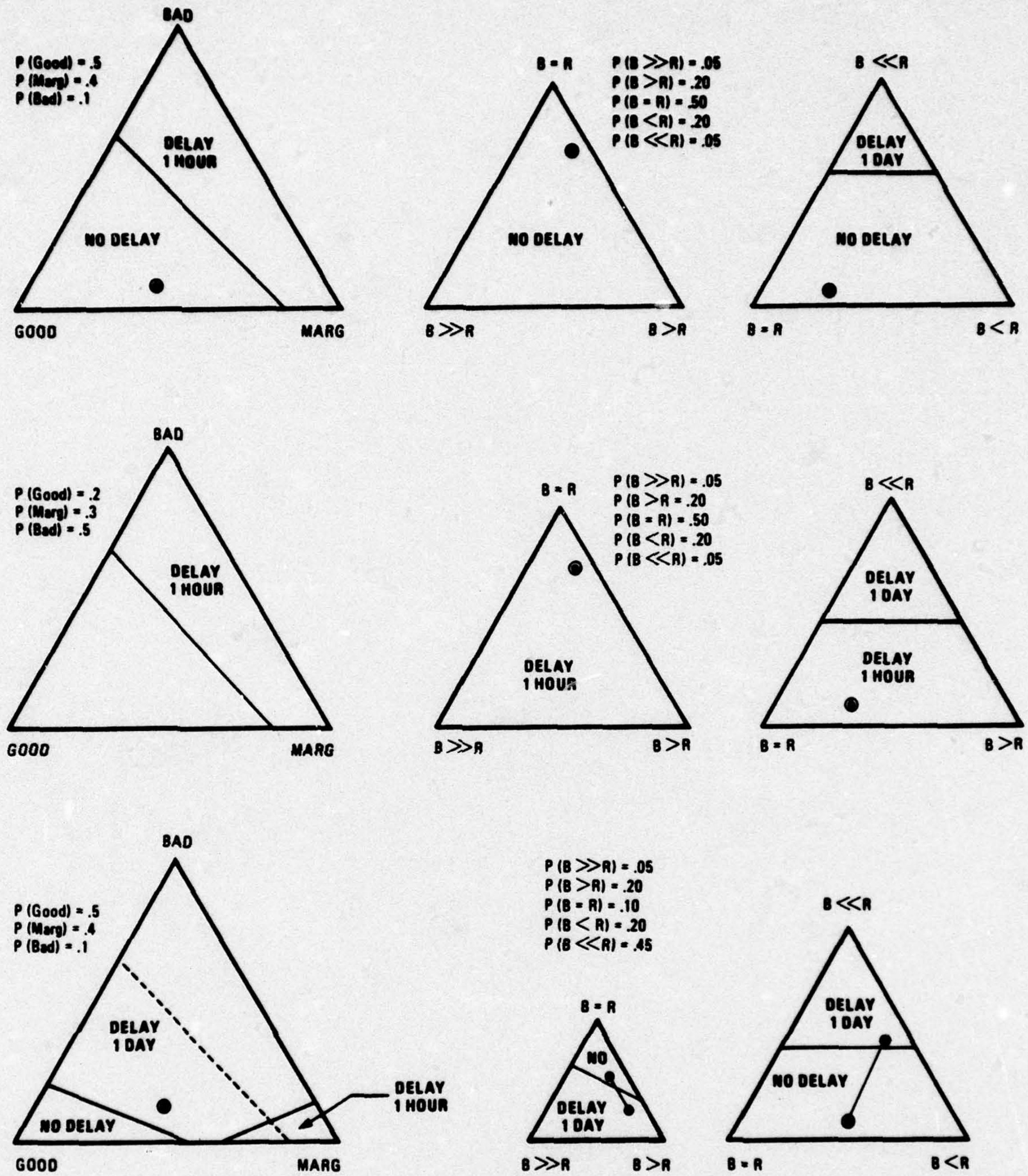

Figure 3-12

ALTERNATIVE STRIKE TIMING MODEL – GRAPHIC DISPLAY

IMPORTANCE WEIGHT

Actions \ Weather	Good	Marg	Bad
No Delay	0	-35	-100
Hour Delay	-50	0	-40
Day Delay	-80	-70	0

.33

Actions \ Force Readiness	B>> R	B > R	B=R	B < R	B << R
No Delay	0	0	0	0	-100
Hour Delay	-3	-5	-10	-20	-90
Day Delay	-10	-20	-40	-50	0

.67

Table 3-5: ALTERNATIVE STRIKE TIMING MODEL – VALUE TABLES

The investigation into the generalized use of the Aid resulted in the identification of the primary criteria that should be met to use the Execution Aid. First, states should be independent of actions. Second, each action's value should be a function of the states. These conditions appear to be met by several tactical decision situations, and an examination of the ONRODA scenarios revealed that the strike timing decision situation met these criteria. An adaptation of the Execution Aid to this decision situation required a method to model graphically several tiers of conditioning events. This requirement was met by using several triangles, and initially one triangle was used for each event tier. A further investigation revealed that the problem could be reformulated in a way that provided an easier value elicitation by using the cutting-plane method to treat more than three states at one of the conditioning tiers. Further investigation of this situation is required to determine which formulation of the problem is the more desirable. However, we can conclude at this time that one of these formulations will lead to wider applicability of the Execution Aid to situations other than the ASM threat as a tactical contingency.

3.4.2 <u>Tactical grid for resource allocation</u> - The investigation described in Section 3.4.1 was concerned with identifying a more generalized use of the properties of the prototype Execution Aid. By contrast, this Section reports the results of an investigation of a more generalized use of the underlying principles of probability and utility theory *in aids for task force commanders.* Accordingly, we did not restrict our investigation to situations where probability thresholds were appropriate. In this investigation, we developed a prototype software program of a new aid that could assist a task force commander to analyze a problem such as allocating fighter sorties to targets. This section describes this aid in the context of a decision action in assigning fighter sorties to targets in the "Amphibious Warfare Scenario" (Rowney, [1975]).

In this example, the Commander of the Supporting Naval Forces (CSNF) in the amphibious scenario must decide how to allocate his sixty-four fighter/attack aircraft among the following nine targets:

1. Greyport Airfields
2. Greyport Seaport
3. Close air support (CAS) at the Blue FEBA (FEBA 1)
4. CAS at the Grey FEBA (FEBA 2)
5. Armed recce
6. Fighter sweeps
7. Orange aircraft re-supply
8. The highway and train bridge
9. Task force defense--CAP/SUCAP

The Commander must consider the multiple mission requirements: to support the landing forces, to provide task force defense, and to limit damage in Grey. This decision must be made during each of the major phases of the amphibious operation, namely, pre-assault, assault, and post assault. Figure 3-13 shows a map of the area, with several of the targets identified.

The principles of probability and utility theory can be used in this situation to determine the expected value of assigning attack sorties to the targets thereby contributing to the preparation of a target assignment list. This is done according to the procedure described in Table 3-6. The expected net value of assigning a single sortie to a target is calculated by subtracting the expected loss from assigning the sortie to the target from the expected value of the destruction done by the sortie against the target. The expected loss is calculated by multiplying the value of the sortie times the probability that it will be lost. The expected value of the destruction is calculated by multiplying the value of the target, which is a weighted value that considers several objectives, by the probability that a sortie will destroy the target. The net value of assigning a second sortie to the target is calculated by a similar method except that the value of the target is reduced by the expected destruction from the first sortie. The value of assigning a third sortie is calculated considering the expected damage done by the first two sorties, and so forth. For example, the incremental value of assigning each of 1, 2, and 3 sorties to a target may be calculated as shown below:

	INCREMENTAL EXPECTED VALUE OF TARGET													−	EXPECTED LOSS					=	INCREMENTAL NET EXPECTED VALUE
Sortie Number	Weighted Value	X	Probability of Destruction	X	Reduction for Previous Destruction	=	Expected Value								Sortie Value	X	Probability of Loss	=	Expected Loss		
1	50		.20		1		10								10		.15		1.5		8.5
2	50		.20		1 - .20		8								10		.15		1.5		6.5
3	50		.20		$(1 - .20)^2$		6.4								10		.15		1.5		4.9

Table 3-7 shows the inputs used in the target-selection problem in the "Amphibious Warfare Scenario." The top table shows the relative values assessed for each target along each objective. The second table shows the importance weights for each objective. The third table shows the probability that a single sortie (a sortie is defined as two attack aircraft in this problem) will destroy the target.

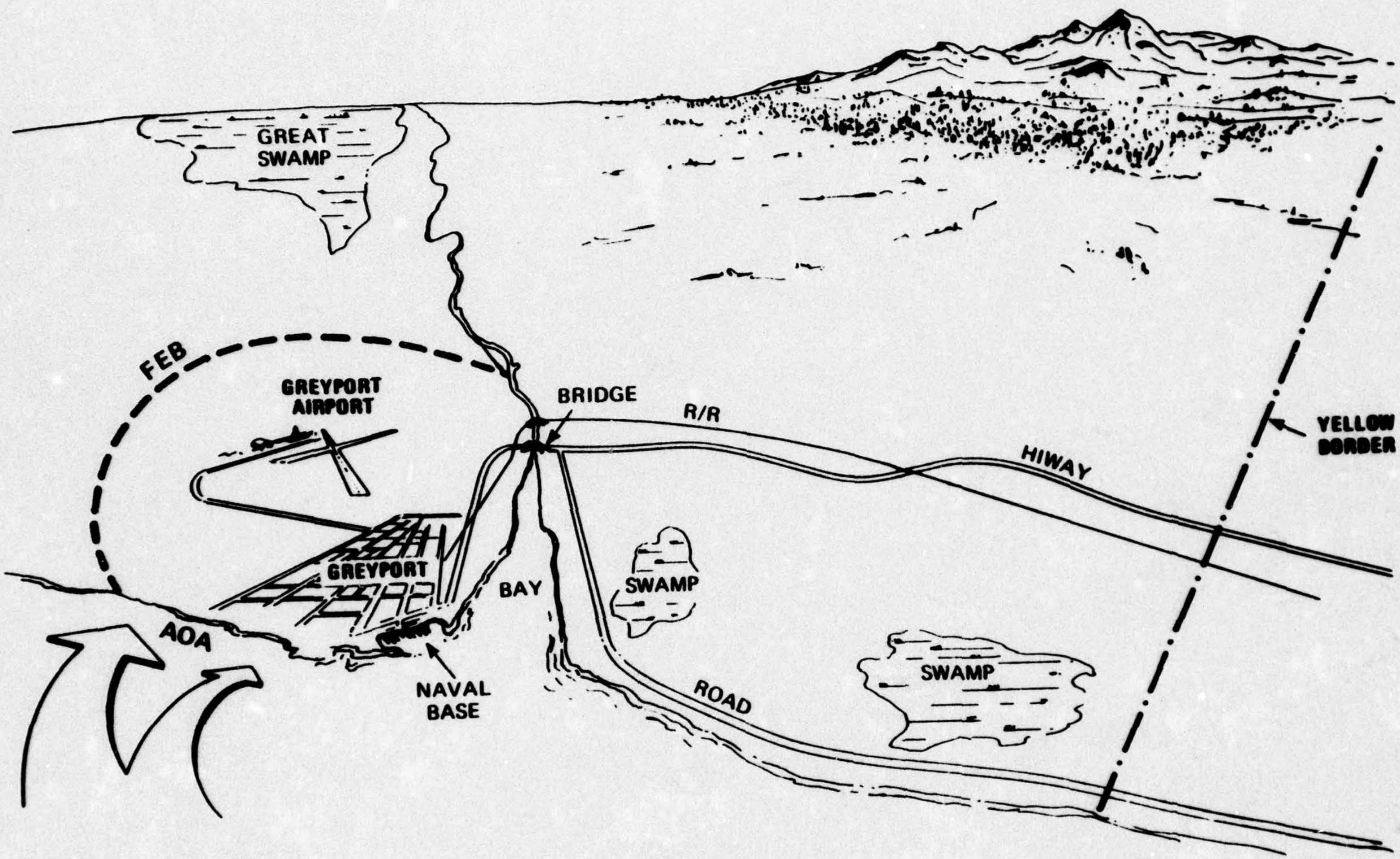

Figure 3-13

TARGETS IN THE AMPHIBIOUS WARFARE SCENARIO

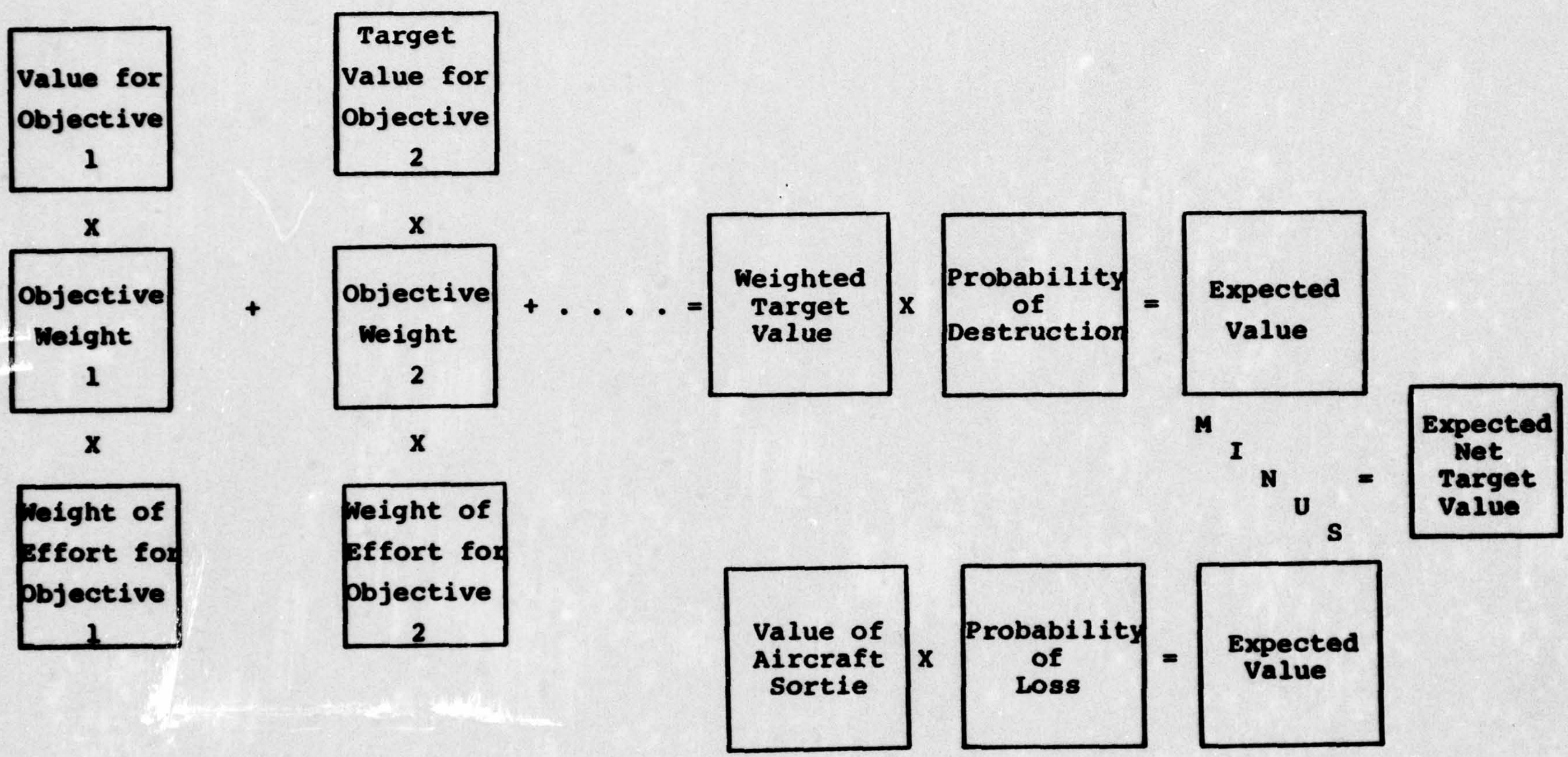

Table 3-6: EXPECTED NET TARGET VALUE CALCULATION – FIRST SORTIE

TARGETS / OBJECTIVES	AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
	TARGET VALUE								
PRE-ASLT	100	90	0	90	10	90	10	0	0
ASSAULT	85	75	100	5	15	20	40	10	0
POSTASLT	50	15	100	90	80	50	25	85	0
TF DEF	40	25	0	0	0	10	5	0	100
DAM LIM	0	0	55	50	30	30	90	20	100

OBJECTIVE	WEIGHT
PRE-ASLT	90
ASSAULT	100
POSTASLT	95
TF DEF	90
DAM LIM	50

PROB. OF DESTRUCTION OF TARGET

	AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
PROB	19	20	34	15	52	45	32	12	45

PROB. OF AIRCRAFT SORTIE LOSS

	AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
PROB	6	1	3	2	2	10	3	5	1

VALUE OF DELIVERY SYSTEM

[illegible]

Table 3-7: TARGET SELECTION PROBLEM – INPUTS

The fourth table shows the probability that a sortie would be lost if assigned to each target. The fifth (bottom) table is an assessment of the value of a sortie, expressed in the same units of value as the top table. These inputs will remain constant during all three phases of the operation: pre-assault, assault, and post-assault. The final required input, the weight of effort devoted to each objective, however, will be different in each phase of the operation.

Table 3-8 shows the weight of effort input for the pre-assault phase and the output calculated for this phase. The major effort is devoted to carrying out the assigned pre-assault mission, and minor effort is devoted to task force defense and damage-limiting in Grey. The second table displays the incremental value of assigning sorties to the targets (calculated as explained above). Based on this information, the CSNF can develop his target list and sortie assignments to maximize the net expected value by assigning sorties to targets with the largest positive values.[10] One optimal allocation of the 32 sorties is shown by the circled entries in the target/sortie value table. This optimum allocation, which assigns eight sorties to the airport, seven to the seaport, and so forth, is obtained by assigning the first 31 sorties so as to obtain incremental net value gains of three or more and by assigning the 32nd sortie to a target that has an incremental gain of two. The third table shows the percent of target damage that can be expected for any assignment of sorties. For example, for the optimal assignment described above, the eight sorties assigned to the airport are expected to cause an 85% level of damage against this target, the seven sorties assigned to the seaport are expected to cause a 79% level of damage against this target, and so forth. The bottom table shows the damage expected to be sustained by the sorties with the target assignments. For example, with the optimal allocation from above, there is a 64% chance of losing a sortie over the airport, a 7% chance of losing a sortie over the seaport, and so forth. The CSNF may wish to consider these items as well in making the sortie allocation.

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[10] Integer programming routines, such as those described in Chapter 11 of Wagner (1970), could be used to optimize the solution, but such a feature is not included in the present version of this Aid. Note also the current SRI (Rowney) investigation to develop an air warfare engagement outcome model.

DISTRIBUTION OF EFFORT

PRE-ASLT	75
ASSAULT	0
POSTASLT	0
TF DEF	15
DAM LIM	10

TARGET/SORTIE VALUE

SORTIE NO. \ TARGET	AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
S 1	12	12	26	1	6	28	18	1	8
S 2	10	9	17	1	3	15	8	0	4
S 3	8	8	11	0	1	8	4	0	2
S 4	6	6	7	0	1	4	2	0	1
S 5	5	5	5	0	0	2	1	0	1
S 6	4	4	3	0	0	0	0	0	0
S 7	3	3	2	0	0	0	0	0	0
S 8	2	2	1	0	0	¯1	0	0	0
S 9	2	2	1	0	0	¯1	0	0	0
S 10	1	2	0	0	0	¯1	0	0	0
S 11	1	1	0	0	0	¯1	0	0	0

PERCENT TARGET DAMAGE

NO. SORTIES \ TARGET	AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
S 1	19	20	34	15	52	45	52	12	45
S 2	34	36	56	28	77	70	77	23	70
S 3	47	49	71	39	89	83	89	32	83
S 4	57	59	81	48	95	91	95	40	91
S 5	65	67	87	56	97	95	97	47	95
S 6	72	74	92	62	99	97	99	54	97
S 7	77	79	95	68	99	98	99	59	98
S 8	81	83	96	73	100	99	100	64	99
S 9	85	87	98	77	100	100	100	68	100
S 10	38	39	98	30	100	100	100	72	100
S 11	90	91	99	83	100	100	100	75	100

PERCENT SORTIE DAMAGE

NO. SORTIES \ TARGET	AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
S 1	8	1	3	2	2	10	3	5	1
S 2	16	2	6	4	4	20	6	10	2
S 3	24	3	9	6	6	30	9	15	3
S 4	32	4	12	8	8	40	12	20	4
S 5	40	5	15	10	10	50	15	25	5
S 6	48	6	18	12	12	60	18	30	6
S 7	56	7	21	14	14	70	21	35	7
S 8	64	8	24	16	16	80	24	40	8
S 9	72	9	27	18	18	90	27	45	9
S 10	30	10	30	20	20	100	30	50	10
S 11	68	11	33	22	22	110	33	55	11

Table 3-8: TARGET SELECTION PROBLEM – PRE-ASSAULT PHASE

Table 3-9 shows how the target/sortie value changes as the weight of effort changes in the assault and post-assault phases of the operation. Based on these revised values, new optimal allocations, such as those circled in the tables, are obtained. For instance, the seaport is a high-value target for the pre-assault and assault phases, but not in the post-assault phase. On the other hand, FEBA 2 is a low-value target for the pre-assault phase, but it is a high-value target for both the assault and post-assault phases. The percent target damage and sortie damage, however, do not depend upon the weight of effort and, therefore, are the same in all phases of the mission (these quantities are shown in the bottom two tables of Table 3-8).

This example illustrates that the principles of utility and probability theory can be combined with an engagement outcome model into an aid to assist the task force commander in real-time decision situations (in this case, to prepare a target list for air strike implementation). The on-the-spot nature of this aid is emphasized because we feel that it can be used in a short-lead-time situations. In fact, the example displayed above required only a few hours to build the model from scratch and enter all of the data into an IBM 5100 micro-computer. Changes in the weights to change from the pre-assault to assault to post-assault phases were accommodated instantaneously.

3.4.3 Status and conclusions - We have identified an interactive graphic software specification for the multiple-triangle display used in the strike-time decision (Section 3.4.1), but no computer software has been developed. In addition, we have identified the specification for a resource allocation aid, described in Section 3.4.2, and have developed a prototype software program of this aid for the IBM 5100 portable microcomputer. This software prototype was demonstrated at the Operational Decision Aids contractors' meeting held in May, 1976.

The results of the investigation into the generalized use of decision analysis aids for the task force commander's execution phase decisions indicate that tactical aids can be developed for other than ASM threat situations. These aids, however, will take a form slightly different from the Execution Aid that was developed within the context of the ASM threat situation.

At this point in our investigation, decision analysis appears most applicable in the area of tactical response to contingency situations. Our investigation indicates that probability thresholds have general applicability to situations in which states are probabilistically independent of actions and the value of an action can be assessed directly as a function of the states. Several task force tactical situations appear to meet the conditions, where major actions may be disrupted by uncertain events. It

DISTRIBUTION OF EFFORT

PRE-ASLT	0
ASSAULT	75
POST ASSAULT	0
TF DEF	15
DAM LIM	10

ASSAULT

SORTIE NO. \ TARGET		AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
S	1	13	13	1	9	4	29	6	0	8
S	2	10	10	0	8	2	15	3	0	4
S	3	8	8	0	7	1	8	1	0	2
S	4	7	6	0	6	0	4	0	0	1
S	5	5	5	0	5	0	2	0	0	1
S	6	4	4	0	4	0	0	0	0	0
S	7	3	3	0	3	0	0	0	0	0
S	8	2	3	0	3	0	-1	0	0	0
S	9	2	2	0	2	0	-1	0	0	0
S	10	1	2	0	2	0	-1	0	0	0
S	11	1	1	0	2	0	-1	0	0	0

DISTRIBUTION OF EFFORT

PRE-ASLT	0
ASSAULT	0
POST ASSAULT	60
TF DEF	30
DAM LIM	10

POST-ASSAULT

SORTIE NO. \ TARGET		AIR P	SEA P	FEBA1	FEBA2	A REC	SWEEP	RESUP	BRIDG	CAP
S	1	7	3	20	9	24	15	10	5	14
S	2	5	2	13	7	12	8	5	5	7
S	3	4	2	9	6	5	4	2	4	4
S	4	3	1	6	5	3	2	1	4	2
S	5	2	1	4	4	1	0	0	3	1
S	6	2	1	2	3	0	0	0	3	1
S	7	1	1	1	3	0	-1	0	2	0
S	8	1	1	1	2	0	-1	0	2	0
S	9	1	0	0	2	0	-1	0	2	0
S	10	0	0	0	2	0	-1	0	1	0
S	11	0	0	0	1	0	-1	0	1	0

Table 3-9: TARGET SELECTION PROBLEM – ASSAULT AND POST-ASSAULT PHASES

appears, though, that such situations require a slightly different form of the prototype Execution Aid, one that can accommodate several tiers of conditioning events. It also appears that such situations are characterized by states whose probabilities can be assessed directly, without a Bayesian hierarchical model for indicators. While further investigation is required before the exact range of applicability of this additional form of the Aid can be determined, we can conclude, at this time, that there is a wider applicability of the prototypical aid to situations other than defense against ASM threats.

Decision analysis principles also appear to be applicable to certain other task force decision problems. In particular, our investigation indicates that decision analysis principles of utility and probability theory can be formulated into an aid that can be used on-the-spot to allocate resources, for example, to assign attack sorties to targets. This aid, however, varies significantly from the prototype Execution Aid. In particular, the allocation aid does not provide guidance in terms of probability thresholds for actions, but rather provides guidance on the expected net value for different allocations of a resource. We feel that this aid may be applicable to a lesser, although important, class of task force decision situations than the Execution Aid, but that it does demonstrate an expanded application of decision analysis principles to a tactical commander's execution-phase decisions.

Further investigation is needed to determine definitively the range of applicability of these decision aids to tactical decision problems, and such an effort is proposed as a future task. However, we have informally examined the task force commander's execution-phase decision situations presented in three documents, Payne et al. (1974), Payne and Rowney (1975), and Rowney (1975), and have tentatively concluded that the decision aids we have identified are applicable in some form to at least fifteen of the situations presented. This inquiry is described in Appendix A of this report and will be expanded under a proposed contract phase.

4.0 SUMMARY OF ACCOMPLISHMENTS, CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary of Accomplishments

1. An evaluation questionnaire, based on a list of desired aid characteristics, was developed for use in the pilot test. This questionnaire proved to be a convenient and efficient instrument for recording the subjects' judgments about the prototype Execution Aid.

2. The range of "enemy" ASM threats was modeled in a form that could be incorporated into the Execution Aid. These threats were both the small-scale air/submarine threat and the large-scale ASM attack system (containing air, surface, and subsurface attack elements). The modeling form consisted of a hierarchical tiering of threat activity and a list of indicators of "enemy" intent, with the air/submarine model only implemented in computer-graphic software.

3. A pilot-test procedure, consisting of a sequence of off-line (view-graph) and on-line (interactive computer-graphic) interactions was developed. This procedure proved to be an effective way to both enhance comprehension of the aid and facilitate its use by the subjects tested.

4. Pilot testing was conducted, and the conceptual acceptance of the Execution Aid was determined. In addition, the pilot testing identified areas for software refinement.

5. Based upon the pilot test, modifications were made in the interactive computer-graphic Aid software.

6. A user's manual is being prepared for the computerized Execution Aid.

7. An investigation into methods of modifying the Aid's display to accommodate more than three state hypotheses was completed. The software modifications necessary to utilize this feature were identified, but they have not yet been implemented.

8. Initial investigations have been made into methods of incorporating explicit considerations of time and risk into the Aid with inconclusive results at this writing.

9. A method to display graphically more than one tier of conditioning events has been identified.

10. A resource allocation aid that utilizes decision analytic principles has been developed. Prototype computer software has been developed for this aid on the portable IBM 5100 microcomputer.

11. The usefulness of a decision aid in situations other than reaction to the ASM threat has been established.

12. A tentative matching of prototype decision aids to task force decision situations has been performed.

4.2 Conclusions

Our research, development, and testing to date has resulted in several conclusions about both the acceptability and the range of application of decision analysis to a Navy task force commander's mission execution decisions.

The results of the pilot testing effort indicate that the concepts involved in our decision analytic Execution Aid are acceptable to Navy task force commanders. These results lead us to conclude that the prototype Aid is now ready to undergo more thorough evaluative testing in a controlled experiment.

The investigations of the ASM threat indicate that this threat can be adequately modeled in a Bayesian hierarchical analysis and the Aid can usefully monitor the threat as it develops.

The investigations into the generalized use of the Aid indicate that it is applicable to a broader class of decision situations than those involving ASM threat alone. In particular, the Aid appears to be applicable to a wide range of contingencies, that is, uncertain events that might warrant a change in operational plan. The probability threshold concept appears to be especially applicable to contingency situations in which state probabilities are independent of the possible actions and value is a function of the action/state combinations.

Finally, it appears that it is possible to extend the graphic display of the probability space to consider more than one tier of conditioning events and more than three state hypotheses within a tier.

4.3 Recommendations

In our view, the Operational Decision Aids project has reached a point in time when the presently identified decision analytic tools warrant some form of systematic evaluation of their potential usefulness beyond their conceptual acceptance. At the same time, it appears prudent to continue a general investigation of the decision analysis technology for the purpose of identifying an increasing number of promising aids embodying proven properties of the methodology. Based upon our current research, we have identified the following areas as promising for the future testing, research, and development of decision analytic aids for Navy task force operations.

4.3.1 Decision aid test and evaluation - In order to establish the usefulness of the Execution Aid, we feel that it is important to perform a small-scale controlled simulation experiment. Such an experiment can provide many of the useful insights of a large-scale simulation at a much lower cost. In addition, a Fleet Operational Investigation of the emerging decision aid prototypes is recommended as a complementary and synergistic ODA project undertaking. Based on several fleet inquiries as to the purpose and objectives of the ODA project, it is deemed appropriate to establish a limited or controlled fleet evaluation of those prototype operational decision aids that have achieved at least conceptual acceptance. The fleet evaluation would be prepared by ONR under the sponsorship of OP-094/943 (Command and Control) in conjunction with OP-098/983 (Test and Evaluation), and the prototype decision aids would be demonstrated for operational feasibility short of a formal technical and operational evaluation. The major purposes of the investigation are to provide operational identification of the project, to provide a realistic environment for early operational assessment (enabling a better-focused research effort), and to test the degree of potential application of the aid as tactical decision tool.

We also feel that the aid should be given exposure, for the purpose of evaluation, in the Naval training environment. In recent years, the Navy has placed increasing emphasis on the use of its war-gaming and tactical simulation facilities for the purpose of training naval officers to better comprehend and cope with the accelerating sophistication in tactical weaponry and with the corresponding threat to naval forces. The Center for War Gaming at the Naval War College has steadily improved its gaming environment to permit the complex play of multi-dimensional tactical problems in crisis or combat situations that are realistically portrayed

to tactical decision makers. The decision environment generated by the war gaming facility offers a rich integration of all significant factors of own force, enemy force, and environmental conditions that are dynamic and interactive and are encountered by tactical decision makers in the course of task force operations. The evolving system is highly flexible, and by including human decision-making in the war game, it is possible to create tactical decision-making situations most likely to be encountered in real-world operations. Without question, war gaming at this level of sophistication and realism offers an exceptional opportunity for testing and evaluating new system concepts designed to support the command and control of naval forces engaged in crisis or combat situations.

In a similar manner, the tactical simulation facilities of the Fleet Training Centers have been reoriented in recognition of the fast moving tactical situations inherent in the single-dimension warfare areas such as AAW, ASW, and EW where multi-threat conditions exist. Here, as in the war gaming environment at the Naval War College, realistic tactical situations are developed for real-time decision making in which human beings are interacting with command support systems to optimize their decision choices for tactical action. In both settings, we perceive a unique opportunity to observe and to investigate the realistic environment of tactical decision making and thereby determine user requirements. Additionally, and in the case of the War Gaming Center in particular, there is a clear opportunity to integrate promising decision aids into the evolving war gaming system and to evaluate their contribution to the tactical decision environment being generated. As an added bonus, both training situations enjoy high-caliber student participation at an observed competitive level, and this may well provide insight as to where decision-aiding tools of a computer-graphic nature will have maximum utility.

4.3.2 Research and development - In the course of our current investigations, we have identified numerous properties of decision analysis methodology that appear to be applicable to the task force commander's decision environment. In developing the decision aids, we initially focused on combining these elements into a single aid. However, we are now of the opinion that an improved capability can be achieved if future aids are developed in a modular fashion by using elements of decision analysis in various aid combinations appropriate to the decision problem. Consequently, we feel that the following software modules warrant immediate development:

1. A module to perform and display a Bayesian hierarchical analysis.

2. A module to implement the cutting-plane method of modeling more than three state hypotheses.

3. A module for modeling several tiers of conditioning events.

In addition to the development activity described above, we recommend further investigation into the generalized use of the prototype aids and the related area of matching modular aids to task force decision situations. It appears at this time that the various properties of decision analysis used in an independent or combined form (modularity), offer unique potential for the development of powerful decision-aiding tools. Whether a universal decision aid, that is, the more general use of a single aid, or a modular tool tailored through simple combination rules is the more appropriate in application to tactical decision problems requires further investigation and analysis. It is hoped that an examination of a variety of tactical situations (for instance: threat, strike, transit, force positioning, target selection, and so forth) will establish a basis for developing matching principles so that tactical decision tools can be quickly assembled for tactical decision making.

APPENDIX A

MATCHING AIDS TO SITUATIONS

APPENDIX A

MATCHING AIDS TO SITUATIONS

A.1 Introduction

At the direction of the Scientific Officer, we undertook the task of investigating three of the ODA project reports, "ONRODA Warfare Scenario" (Payne and Rowney [1975]), "Amphibious Warfare Scenario" (Rowney [1975]), and "The Naval Task Force Decision Environment" (Payne et al. [1974]), to identify task force commander decision situations to which the prototype decision aids described in this report would apply. The investigation has been informal and requires further work before definitive conclusions can be reached. However, we can tentatively conclude that the decision aids described in this report are applicable, to some extent, to at least fifteen of the decision situations that were investigated. This appendix serves as the starting point for a more extensive investigation to be conducted under a proposed contract phase.

A.2 Scope of the Matching Investigation

We have limited the scope of this matching investigation to tactical decision situations in which one of the three aids described in this report, the original Execution Aid, the Contingency Aid (see Section 3.4.1 above), and the Tactical Grid (see Section 3.4.2 above), or some variant of these aids could be applied. While other decision situations may be important to the task force commander, we feel that decision analysis may prove more beneficial to situations in which some form of the Contingency Aid (either the Execution Aid or the Contingency Aid of Section 3.4.1) applies.

In particular, we feel that contingency situations involving naval mission execution offer a more fruitful area for decision analytic investigation than mission planning decisions. Previous investigations revealed that it was difficult to identify initial planning decisions that were rich enough to support a decision analysis effort beyond planning for allocation-type problems. In contrast, contingency situations appear to be characterized by value conflicts and by a wide range of action possibilities that make them fruitful areas for application of decision analysis in tactical environments. Within a class of contingency decisions, it is possible to develop decision thresholds based on events, such as "Do not shoot until you are fired upon" or "Avoid confrontation at all cost." In some situa-

tions these thresholds may provide useful guidance, and in those situations decision analysis is not very applicable. However, in many situations these types of thresholds are too rigid to be useful as action guidelines, and here decision analysis can be helpful by providing probability thresholds that allow the combined effect of many combinations of data to indicate the preferred action. Finally, probability thresholds for actions may be either dependent or independent of the specific mission context in which a choice must be made. Computerized decision aids appear to be most applicable for developing and displaying probability that is independent of the mission context because, in such cases, useful computerized models can be developed in advance.

Thus, our investigation of the decision situations described in the three referenced documents focused on classifying mission-execution-phase decisions according to the applicability of probability thresholds and the degree of scenario independence. Secondarily, the situations were classified according to the applicability of several of the specific analytic options available in the aids under development.

A.3 Matching Analytic Options to Situations

The first step in matching potential decision aids to situations is to match the analytic options that are offered in the aids to the situations. Table A-1 displays the results of our investigation of nine situations in the ONRODA scenario, eight situations in the Amphibious scenario, and six mission-execution-phase decisions from the Task Force Decision Environment report. These situations were chosen on the basis of a high expectation of finding a match between the situations and the analytic options. A match between an analytic option and a situation is indicated by an X in the row of the analytic option and the column of the situation. For example, the first decision situation, the choice of a course of action in the ONRODA scenario, is felt to support the use of probability thresholds derived from an analysis that contains several tiers of conditioning events with more than three states, a direct assessment of state probabilities, and multiple conflicting values. This chart served as the basis for matching the aids to situations as explained below.

A.4 Matching Decision Aids to Situations

An examination of Table A-1 reveals that several combinations of analytic options are applicable over a wide range of decision situations. These combinations, which correspond roughly to the prototype aids that we have developed, can thus be used to describe decision aids that are applicable to a number of situations. These combinations are as follows:

ANALYTIC OPTIONS	ONRODA WARFARE SCENARIO									AMPHIBIOUS WARFARE SCENARIO								T.F. DECN. ENVIRONMENT (Execution-Phase Decisions)					
	A1 COURSE OF ACTION	A2 LAUNCH POINT	A3 TARGET SELECTION	A4 DEFENSIVE ACTION	A5 ASM THREAT	A6 STRIKE TIMING	A7 RECCE TIMING	A8 REQUEST ASSISTANCE	A9 GATHER INFORMATION	B1 TRANSIT-FORCE POSITIONING	B2 TRANSIT-THREAT MONITORING	B3 ASSAULT TIMING	B4 FORCE POSITIONING	B5 TARGET SELECTION	B6 REQUEST ASSISTANCE	B7 RULES OF ENGAGEMENT-TO SUBS	B8 RULES OF ENGAGEMENT-INTERPRET	C1 D.23 CHANGE TIMING	C2 D.24 RESTRUCTURE FORCES	C3 D.26 COMMIT RESERVES	C4 D.28 PLAN FOLLOW-ON	C5 D.29 DIVERT FORCES	C6 D.30 DISCONTINUE OPS.
PROBABILITY THRESHOLDS	x	x		x	x	x				x	x	x	x					x	x	x		x	x
SCENARIO INDEPENDENT				x	x	x				x	x	x						x	x				
SINGLE CONDITIONING TIER		x		x	x			x		x	x		x		x	x	x			x			x
SEVERAL CONDITIONING TIERS	x					x	x					x						x	x		x	x	
FEWER THAN 4 STATES				x	x					x	x		x										
MORE THAN 3 STATES	x					x						x						x	x		x	x	
DIRECT PROBABILITY ASSESSMENT	x	x				x		x				x	x		x	x	x	x	x	x		x	x
BAYESIAN PROBABILITY UPDATING				x	x					x	x												
BAYESIAN HIERARCHICAL ANALYSIS				x	x					x	x										x		
MULTIPLE VALUE DIMENSIONS	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
RESOURCE ALLOCATION (SORTIE)																							

Table A-1: MATCHING ANALYTIC OPTIONS TO SITUATIONS

1. Aids that use decision thresholds

    a. Contingency decision aid--Mode 1 (the original Execution Aid)

    b. Contingency Decision Aid--Mode 2 (the generalized Contingency Aid, Section 3.4.1)

    c. Contingency Decision Aid--reduced form

2. Aids that do not use decision thresholds

    a. Tactical Grid--resource allocation (from Section 3.4.2)

    b. Other (undefined) aid

Table A-2 illustrates how these aids match the situations considered.

As discussed in Section 3.4.1, aids with decision thresholds are applicable to decision situations that can be structured so that:

1. The state probabilities are independent of the actions; and

2. The value of the actions can be assessed as a function of the states.

The mode 1 type contingency aid(s), which incorporated features of the original Execution Aid, is most applicable in situations that are:

1. Predictable and scenario-independent enough to model in advance.

2. Characterized by a predictable set of indicators that can be modeled in a Bayesian hierarchical structure and used for probability updating.

3. Characterized by a state space that can be adequately modeled in a single conditioning tier that contains three or fewer states.

Situations such as the "enemy" ASM threat in a crisis setting fall into the category where the mode 1 contingency aid is most useful. Although there may be only a relatively small number of these situations, we feel that they are most important and are undoubtedly contingencies that a Navy task force commander would encounter.

DECISION AIDS	A4 DEFENSIVE ACTION	A5 ASM THREAT	B1 TRANSIT-FORCE POSITIONING	B2 TRANSIT-THREAT MONITORING	A1 COURSE OF ACTION	A6 STRIKE TIMING	B3 ASSAULT TIMING	C1 D.23 CHANGE TIMING	C2 D.24 RESTRUCTURE FORCES	C5 D.29 DIVERT FORCES	A2 LAUNCH POINT	B4 FORCE POSITIONING	C3 D.26 COMMIT RESERVES	C6 D.30 DISCONTINUE OPERATIONS	A3 TARGET SELECTION	B5 TARGET SELECTION	A7 RECCE TIMING	A8 REQUEST ASSISTANCE	A9 GATHER INFORMATION	B6 REQUEST ASSISTANCE	B7 RULES OF ENGAGEMENT - TO SUBS	B8 RULES OF ENGAGEMENT - INTERPRET
CONTINGENCY DECISION AID - MODE 1	X	X	X	X																		
CONTINGENCY DECISION AID - MODE 2					X	X	X	X	X	X												
CONTINGENCY DECISION AID - REDUCED FORM											X	X	X	X								
TACTICAL GRID-RESOURCE ALLOCATION															X	X						
OTHER (UNDEFINED) DECISION AID																	X	X	X	X	X	X

SITUATIONS

Table A-2: MATCHING DECISION AIDS TO SITUATIONS

The mode 2 type contingency decision aid(s) is composed of features that were developed in the generalization sections of this report, especially Sections 3.4.1 and D.5. Namely, this type aid has provisions for multiple conditioning tiers, more than three states within a tier, and multiple dimensions of value, but does not have provisions for Bayesian probability updating or Bayesian hierarchical analysis. This aid is most useful in situations that are:

1. Predictable and scenario-independent enough to model in advance.

2. Not characterized by a predictable set of indicators for Bayesian probability updating (that is, characterized by probabilities that can be assessed directly).

3. Characterized by a complex state space that requires several tiers of conditioning events or more than three states within a tier.

We expect more of the commander's decision situations to fall into this category; however, these decisions may not be as critical as the ones for which the mode 1 aid is appropriate.

Situations in which a reduced form of the aid such as the multi-attribute value tables might be useful involve either simple or uncritical decisions that do not deserve a large analytical effort.

Situations that cannot be adequately modeled in a form that is appropriate for development of probability thresholds require aids different from the contingency type aids described above. One such aid is the Tactical Grid, which is described in Section 3.4.2. This aid requires the decision situation to fit a special form such as allocating attack sorties to targets in target selection decisions. Situations that do not meet any of these requirements need other forms of decision aids, ones which we have not yet identified or defined.

APPENDIX B

TEST PROCEDURE ILLUSTRATIONS

APPENDIX B

TEST PROCEDURE ILLUSTRATIONS

B.1 Scenario Familiarization

A 35 mm slide presentation, supported by a typical staff intelligence (N2) and operations (N3) officer situational brief, was presented to the test subject as a "scene setter" for ONRODA scenario familiarization. The information was presented in a manner calculated to provide the general political-military situation prevailing at the time the Blue commander received his mission directive from higher authority. The subject was permitted time to consider the operational planning phase that followed. The "scene-setter" then proceeeded into the mission execution phase of the scenario and brought the test subject to the point of tactical execution of his mission plan.

At this point, the ASM threat was introduced as a tactical situation of serious concern to the commander, requiring on his part a number of difficult decisions, a need to consider significant changes to mission plan and subordinate tasking, as well as a review of any inhibiting aspects of the rules of engagement as imposed by higher authority.

B.2 Off-line/On-line Interactions

As described in Section 2.3.2, the test procedure involved a series of off-line (vu-graph presentations) and on-line (computer graphic) interactions between the subject and the Aid. The charts used in the off-line presentations successfully communicated the Aid's properties and features to the subject and served to transition the subject to the computer-graphic presentations manifest in the prototype Aid for ease of evaluation.

B.2.1 Off-line presentations - The following visual aids were used off-line to introduce the subjects to the Red ASM threat situation that would be presented in the most reduced form of the Aid: Table B-1 describes the operational concerns within the threat; Table B-2 lists the ASM threat indicators that would appear as the situation developed; and Table B-3 presents a checklist of some of the actions that the subject (serving as the Blue task force commander) might wish to take in response to the developing threat.

The next set of visual aids were used off-line to describe the probability plane to the subjects before

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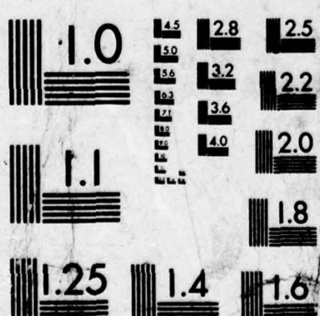


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ROUTINE	-	RED INTENDS TO ENGAGE IN ONLY HIS ROUTINE SURVEILLANCE ACTIVITIES.
FEINT	_	RED INTENDS TO BRING HIS AIR/SUBMARINE COMBINATION TO A FULL STATE OR READINESS BUT STOP SHORT OF ATTACK.
ATTACK	-	RED INTENDS TO ATTACK THE BLUE TASK FORCE USING AN AIR/SUBMARINE COMBINATION.

Table B-1: POSSIBLE RED OPERATIONAL OPTIONS

Political	- Hostile - Normal - Ignoring
National	- General Alert - Theatre Alert - Selective Alert - No Alert
Deployment	- Tactical - Strategic
Surface	- Normal - Attack - Withdraw
Comms	- Increase/High - Normal/High - Increase/Low - Normal/Low
Submarine	- Normal - Multiple
Search	- Yes - No
Targeting	- MW/Int. - MW/Steady - None
Track	- Routine - Attack
Beacon Test	- Yes - No
Guidance Radar	- Yes - No
Command Comms	- Yes - No
Sounds	- Yes - No
Intercept	- Yes - No

Table B-2: RED ASM THREAT INDICATORS

ROUTINE OPERATIONS (Condition 3)	HEDGE (Condition 3)	PREPARE FOR ATTACK (Condition 3)
o Surveillance - World-wide Indications and Warning (I&W) watch - Standard Task Force Recce and Surveillance	o Surveillance - Review I&W tasking - Confirm cover and deception (C&D) plans - Maintain augmented task force recce and surveillance - Reassess threat potential	o Surveillance - Optimize task force recce-surveillance posture - Intensify I&W watch
o Command and Control - Routine information (threat intelligence) flow - Standard tactical doctrine; IAW NWPs - Orders and instructions IAW mission plan	o Command and Control - Modify task force tasking IAW contingency plans - Set condition minimize - Select EMCON - Task Allies support forces - Notify seniors and subordinate commanders of intentions	o Command and Control - Transmit C&D tasking - Deploy ECM forces - Modify EMCON - Select emergency communication plan - Notify all commanders - Reposture task force disposition - Withdraw logistic support forces
o Force Readiness - Strike operations IAW strike plan (Alphas) - Standard AAW-ASW tactical deployment - Task force disposition - 6V1 - Routine logistic operations (UNREP) - ASMD readiness IAW NWP 31-33	o Force Readiness - Reduce strike operations to tactical interdiction - Maintain augmented AAW-ASW - Redeploy surface units IAW threat situation - Maintain high state of logistic readiness	o Force Readiness - Cancel strike operations - Optimize AAW-ASW tactical deployment - Transmit blocking and withdrawal plans - Complete attack preparations - Implement target assignments - Transmit ROE - Modify tattletail tasking

Table B-3: POSSIBLE BLUE RESPONSE OPTIONS

this feature of the Aid was presented in on-line interaction with the graphic terminal. Figure B-1 was used to explain how the triangle represents probabilities, in effect, how to "read" the probability triangle. Figure B-2 was used to display the beginning probabilities that would be used in the computer interaction.

The final set of visual aids was used off-line to introduce the test subjects to the action threshold feature of the Aid before on-line interaction with the full form of the Aid. Table B-4 describes the criteria that might be of concern to the commander in the crisis situation prevailing. These are the criteria used in the computer version of the Aid.

Table B-5 was used to describe how action thresholds are calculated from a value matrix. Figure B-3 in this group illustrates how a threshold equation is displayed in the probability triangle.

Finally, Table B-6 was used to describe the elicitation process, the meaning of the assessments on each value criterion, and the way that the combined value matrix is calculated. The values in Table B-6 are the same as those initially used in the computer-graphic interaction.

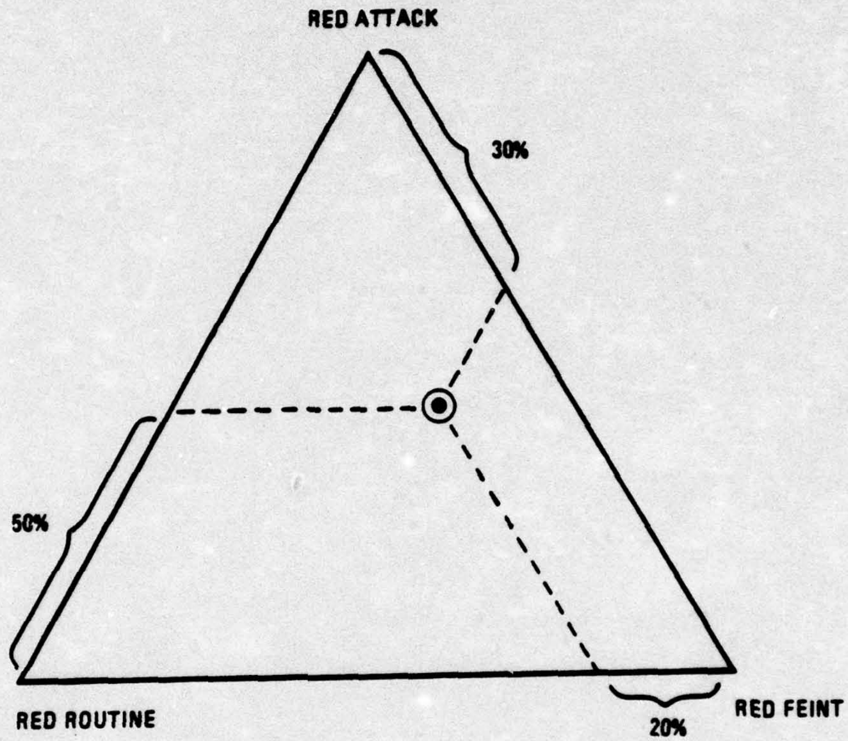


Figure B-1
PROBABILITY PHASE INTERPRETATION

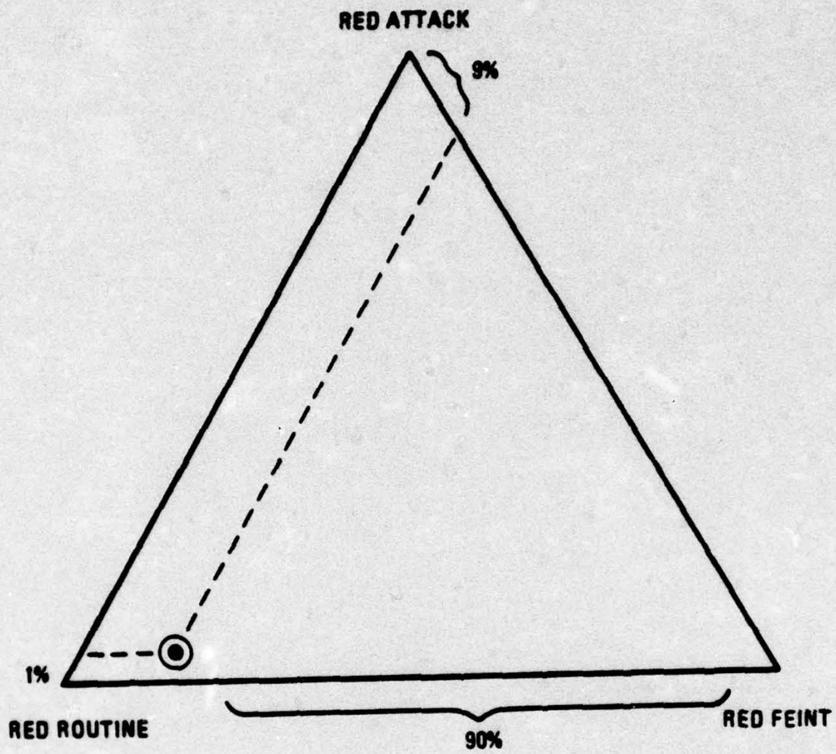


Figure B-2

PRIOR PROBABILITY ASSESSMENT

VALUE CRITERIA

- o MISSION SUCCESS - NEUTRALIZING THE ORANGE AIRFIELD
- o OWN FORCE DAMAGE - SUSTAINING THE MINIMUM AMOUNT OF DAMAGE TO YOUR OWN FORCES
- o RULES OF ENGAGEMENT - CONFRONTATION WITH RED
- o NATIONAL GOALS - AVOIDING OVER-REACTION AND UNDER-REACTION TO THE THREAT

Table B-4: COMMANDER'S CONCERNS

Red Intention / Blue Action	1 Routine	2 Feint	3 Attack
Routine Ops.	-1	-7	-40
Stage	-4	-6	-37

Routine Ops preferred to Stage when:

$$\text{VALUE OF ROUTINE OPS} > \text{VALUE OF STAGE}$$

$$(-1)p_1 + (-7)p_2 + (-40)p_3 > (-4)p_1 + (-6)p_2 + (-37)p_3$$

Table B-5: DECISION THRESHOLD CALCULATION

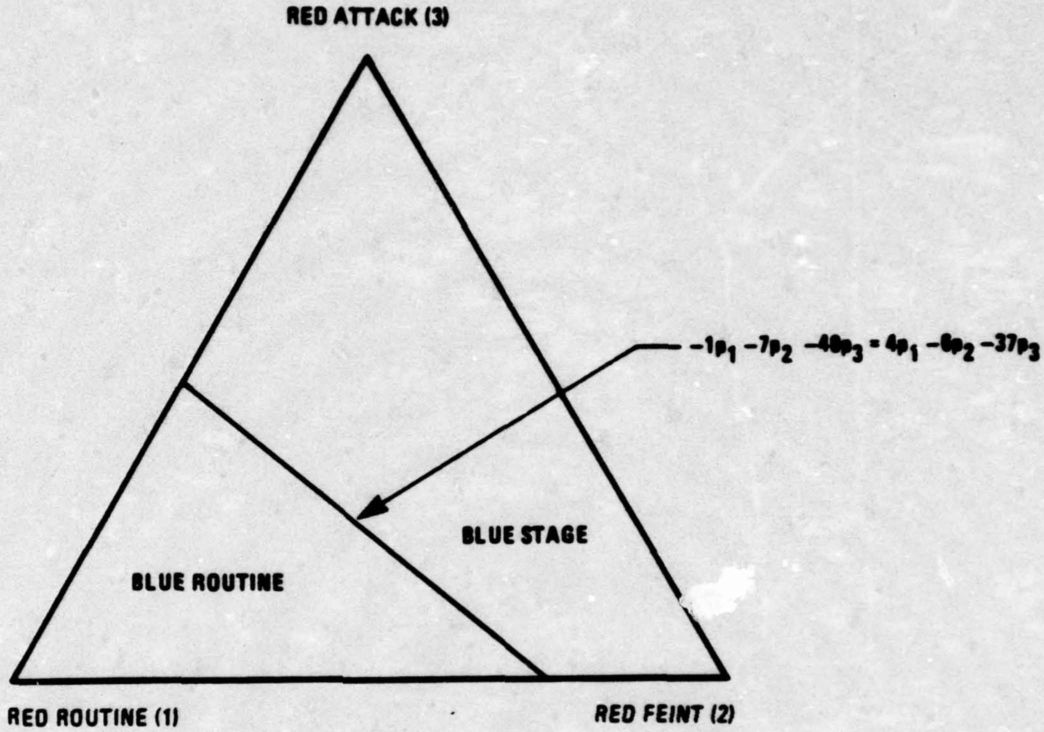


Figure B-3
THRESHOLD DISPLAY

Blue Action \ Red Intention	Routine	Feint	Attack
Routine Ops	-1	-7	-40 ← (0 x .35)+(-100 x .20)+(0 x .25)+(-100 x .20)
Stage	-4	-6	-37
Hedge	-20	-10	-27
Prepare to Attack	-43	-29	-8
Attack	-79	-62	-5

Blue Action \ Red Intention	Mission Success			Own Force Damage			Rules of Engagement			National Goals		
	Routine	Feint	Attack	Routine	Feint	Attack	Routine	Feint	Attack	Routine	Feint	Attack
Routine Operations	0	0	$\boxed{0}$	-3	-20	$\boxed{-100}$	0	-5	$\boxed{0}$	0	-10	$\boxed{-100}$
Stage	-5	-4	-1	-2	-17	-95	-5	-2	0	-5	-5	-90
Hedge	-25	-23	-4	0	-10	-60	-20	0	0	-30	0	-70
Prepare to Attack	-50	-45	-8	-2	0	-15	-60	-30	-1	-50	-30	-10
Attack	-100	-90	-10	-5	-10	0	-100	-80	-5	-90	-40	0
Criterion Importance Weight		35			20			25			20	

Table B-6: MULTI-ATTRIBUTE VALUE MATRIX

APPENDIX C

QUESTIONNAIRE

APPENDIX C

QUESTIONNAIRE

Timeliness of Decision

1. How might the aid specification be modified to enable a faster and/or more complete response to a developing threat?

2. Do you feel the aid would serve to make you more confident of your decision choices having developed tactical options in advance of a contingency?

3. Are you concerned that tactical situations are too dynamic to entrust event planning to a tool that is based on prior planning and preprogramming?

Quality of Decision

1. Do you feel this aid will help a CTF focus on those decision situations that are of primary concern to him?

2. Could there be an assured continuity of expertise inherent in an aid of this type?

3. Would there be an objection to the "documentary" aspect of the aid insofar as a record of tactical action is concerned?

Ease of Operation

1. Do you feel the aid contributes to the essential flow of tactical data, or is it in some way an inhibiting and perhaps unnecessary tool?

2. Perhaps the aid would better serve those staff officers responsible for the functional activities of mission accomplishment, i.e., strike planning, AAW, ASW, etc.

3. Do you feel the CTF would use a decision aid of this type in a tactical situation?

Ease of Understanding

1. Of the three displays, is there any difficulty in comprehension?

2. Would you recommend more or less graphic support?

3. Would you comment on the need for an executive (CTF) aid vis-a-vis those aids the supporting staff might use?

APPENDIX D

INVESTIGATIONS FOR TREATMENT OF MORE THAN THREE STATE HYPOTHESES

APPENDIX D

INVESTIGATIONS FOR TREATMENT OF MORE THAN THREE STATE HYPOTHESES

D.1 Introduction

As stated previously in Section 3.0, the geometry utilized in the current Execution Aid permits only three state hypotheses to be considered in our decision modeling. In response to inquiries regarding situations that could generate the need to consider more than three hypotheses, we undertook an investigation to examine alternative methods. The following sections describe our initial investigations in this area.

D.2 Hierarchical Arrangement of Models

In a hierarchical arrangement of models, the problem is addressed in stages, each of which has its own separate model. For instance, the two threat situations described in Section 2.2 above, that is, the air/submarine ASM threat and the multiple-attack element ASM threat, might be addressed with the hierarchical arrangement of models shown in Figure D-1. At the top level of the hierarchy, an analysis is made of whether it is better to take an action responsive to a single threat, a multiple threat, or no significant threat (status quo). This analysis will contain values and indicators relevant to this higher-order decision. A developing situation will cause the probability point (bug) to enter a decision area such as, "respond to single threat." This event will then trigger the recall and display of the lower-level or subordinate model of the single ASM threat, where the subordinate model contains values and indicators relevant to the analysis of lower-order decisions.

This hierarchical-arrangement-of-models approach is capable of handling more than three states and may be quite natural in many situations, but its structure is not completely general. In particular, it may prove difficult for some decision makers to model their problems in a manner that fits the structural requirements of the hierarchical arrangement and yet still accurately represent the actual situation. This approach does have the desirable feature that each analysis is completely described; that is, nothing is omitted from any display, and there is no theoretical limit to the number of states which can be modeled.

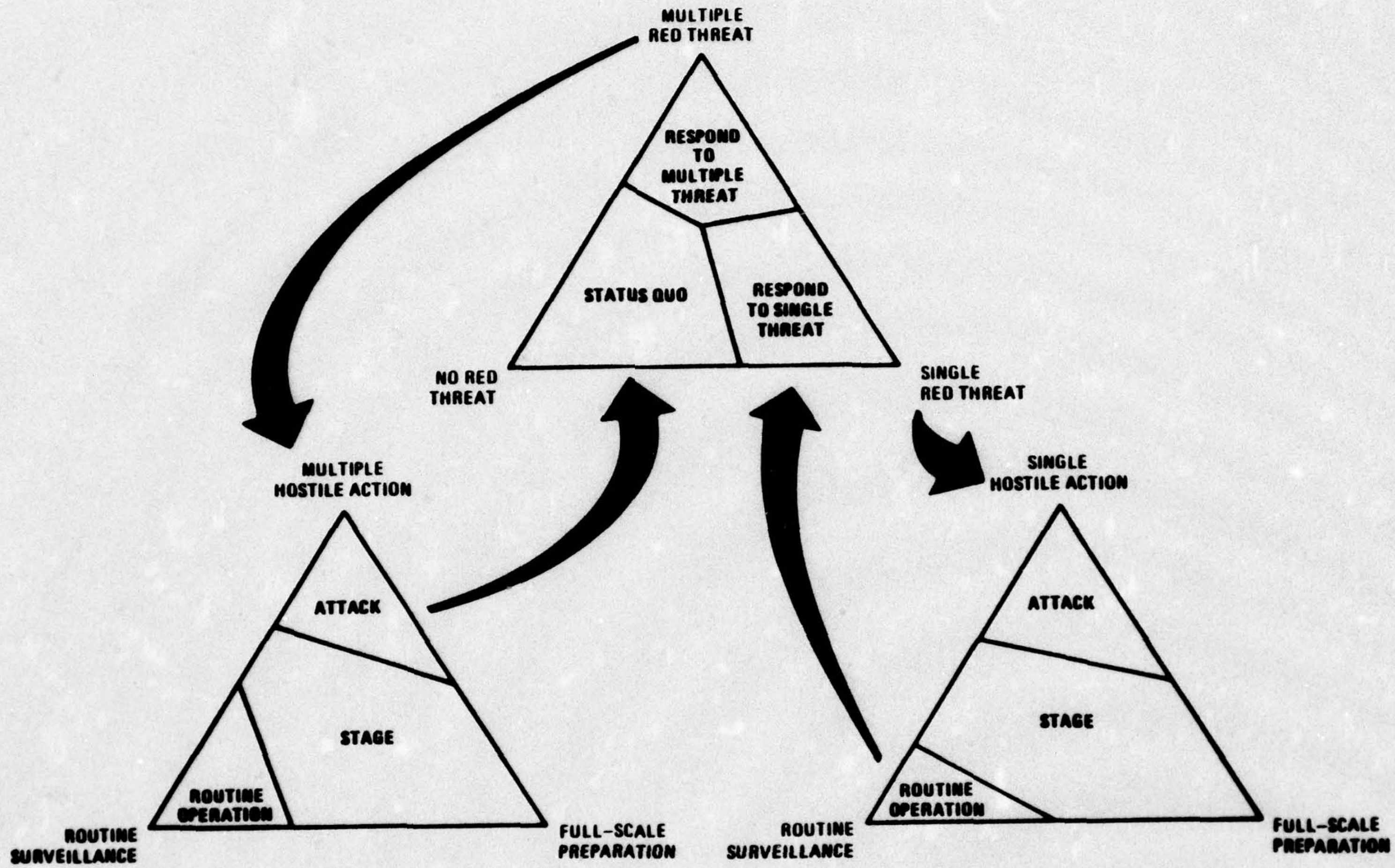


Figure D-1
HIERARCHY OF EVENTS

D.3 Distance-to-Threshold Method

An alternative way to model more than three states is to display the distances from the probability bug to the decision thresholds. A display of the distances to the decision thresholds discards the triangular display entirely, and it does not restrict the analysis to any particular form. The concept and derivation of the distance-to-threshold display are illustrated in Figure D-2. The top figure shows a probability triangle divided into five action regions, "R"; "S"; "H"; "P"; and "A". At the probability point indicated, "P" is the preferred action and the minimum distances to the other action areas are indicated as the lengths of the line segments D_r, D_s, D_h, and D_a. The bottom figure shows the corresponding distance-to-threshold display. The distance to the preferred action is zero, and the distances to the other actions are those calculated as shown in the top figure. Note that although the figure illustrates the concept using only three states, the display of the distances to the thresholds requires only that the distances to the thresholds can be calculated, which does not place restrictions on the number of states.[5]

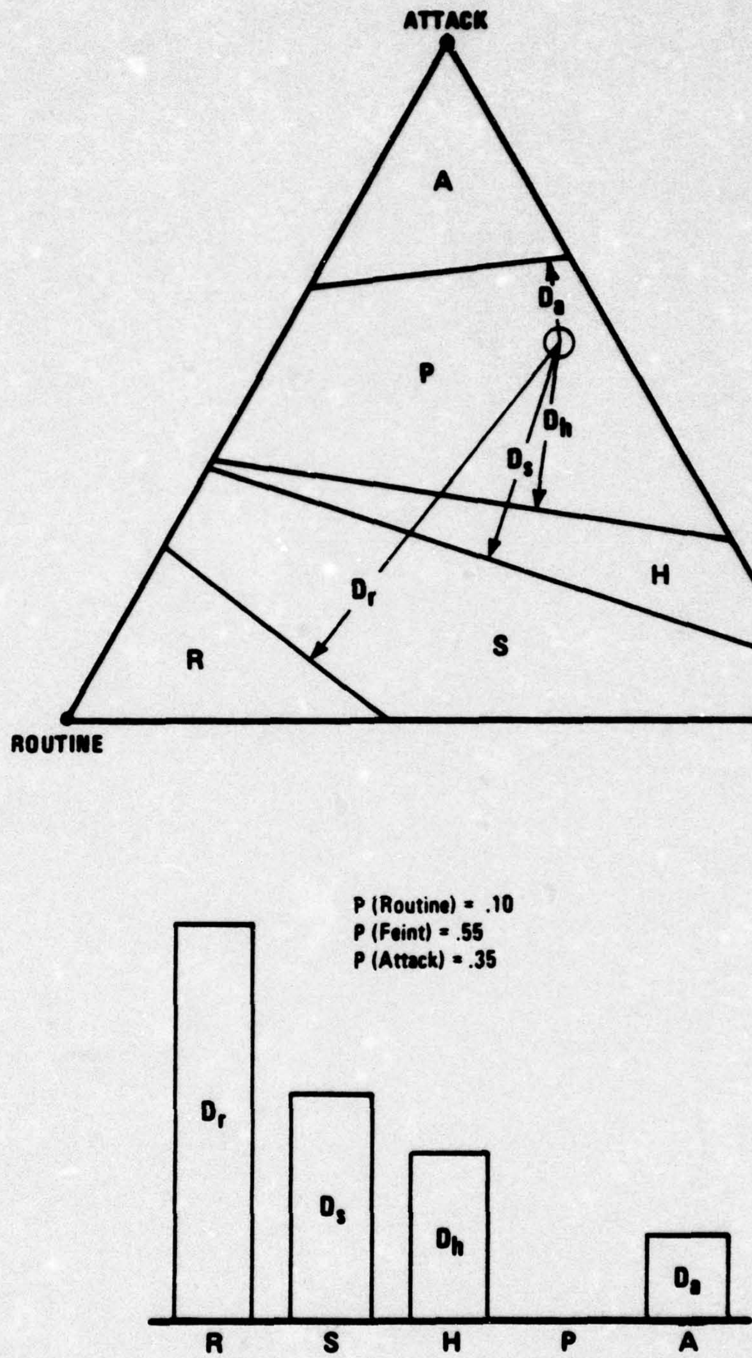
Figure D-3 illustrates the distance-to-threshold display changes as the probability bug crosses into the "A" action area.

People who were familiar with the triangular display form participated in workshop trials using the distance-to-threshold display. These trials revealed that the distance-to-threshold display lacked the user appeal of the triangular display and, more importantly, that the distance-to-threshold display did not communicate the tactical situation as well. Subjects felt that the display did not communicate sufficient information about the situation. In particular, they indicated that it lacked the dynamic and the geometric quality of the triangular form. This is possibly because the distance-to-threshold display does not provide a graphic history of the probabilities, as does the plot of the probability bug. On the whole, this alternative appeared to be undesirable.

D.4 The Probability Tetrahedron

Both the projection method and the cutting-plane method involve the concept of a probability tetrahedron. The probability tetrahedron is a generalization of the proba-

[5] Fishburn, Murphy, and Isaacs (1968) presents an algorithm for calculating distances to thresholds.

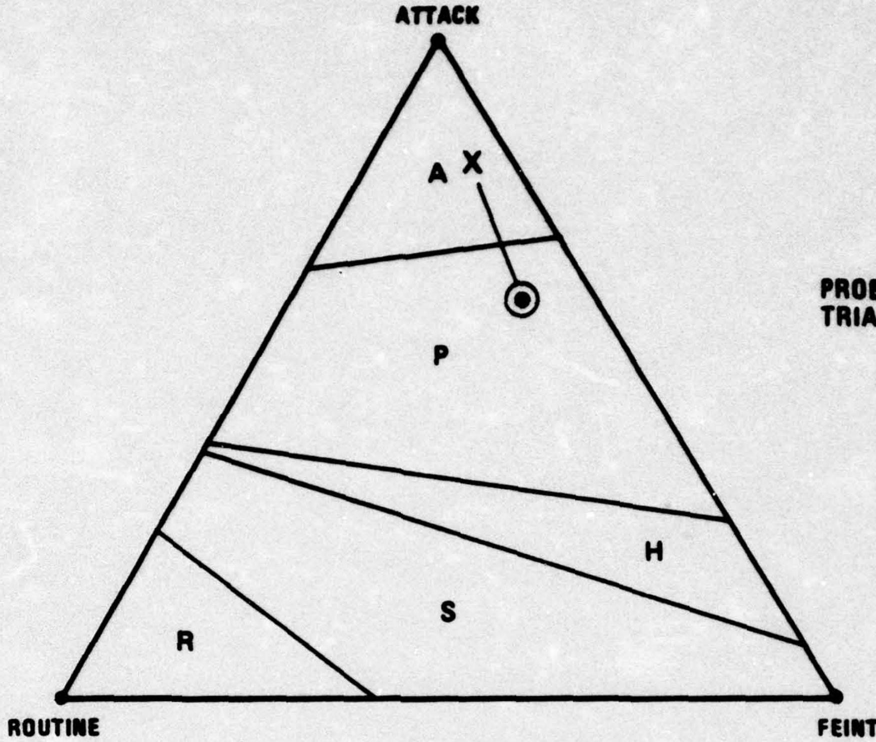


PROBABILITY TRIANGLE

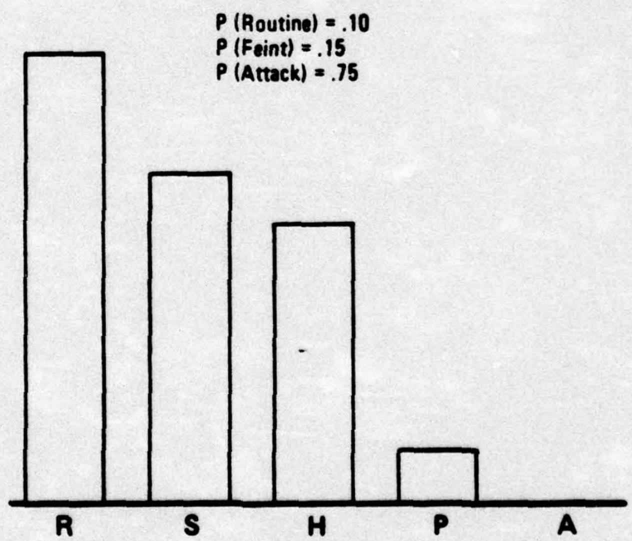
DISTANCE-TO-THRESHOLD DISPLAY

Figure D-2

DISTANCE TO THRESHOLD I



PROBABILITY
TRIANGLE



DISTANCE-
TO-THRESHOLD
DISPLAY

Figure D-3

DISTANCE TO THRESHOLD II

bility triangle, extended to three dimensions and four states of the hypothesis variable (Figure D-4). It is a solid which satisfies the following conditions which are required by the rules of probabilities:

$$p(1) + p(2) + p(3) + p(4) = 1.0$$

$$0.0 < p(1) < 1.0$$

$$0.0 < p(2) < 1.0$$

$$0.0 < p(3) < 1.0$$

$$0.0 < p(4) < 1.0.$$

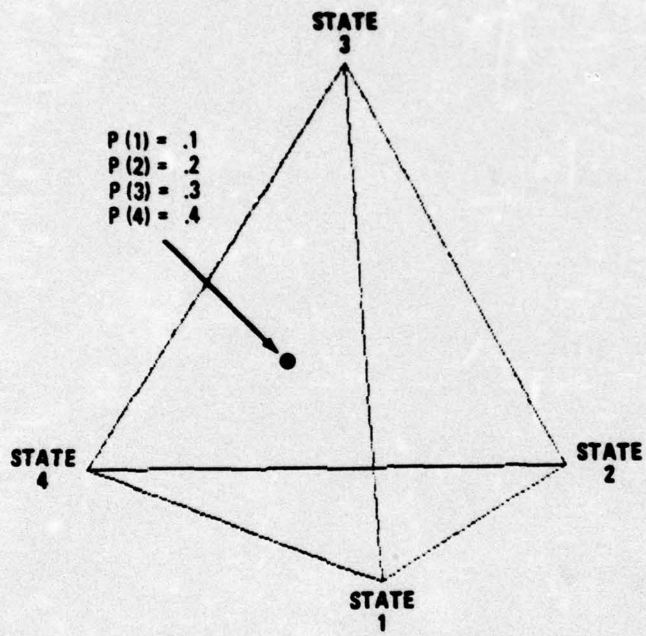


Figure D-4
PROBABILITY TETRAHEDRON

The representation of probability points in the probability tetrahedron is defined in exactly the same manner as the probability triangle. In the probability triangle the probability of any point inside the triangle was defined as the distance of the point from each of the three sides; in

the probability tetrahedron the probability of any point in the volume is defined as the distance of the point from each of the four faces.

One way to describe the position of the probability point (bug) is in terms of four sets of parallel planes, each set parallel to one of the faces of the tetrahedron. For example, one set of planes is parallel to the face of the tetrahedron which is opposite vertex 1 (Figure D-5). Each of these planes represents a different, but constant, probability that state 1 will occur. The plane which is located a tenth of the way from the face to the vertex represents a probability of state 1 which is equal to 0.1, the one which is halfway represents a probability of 0.5, and so on.

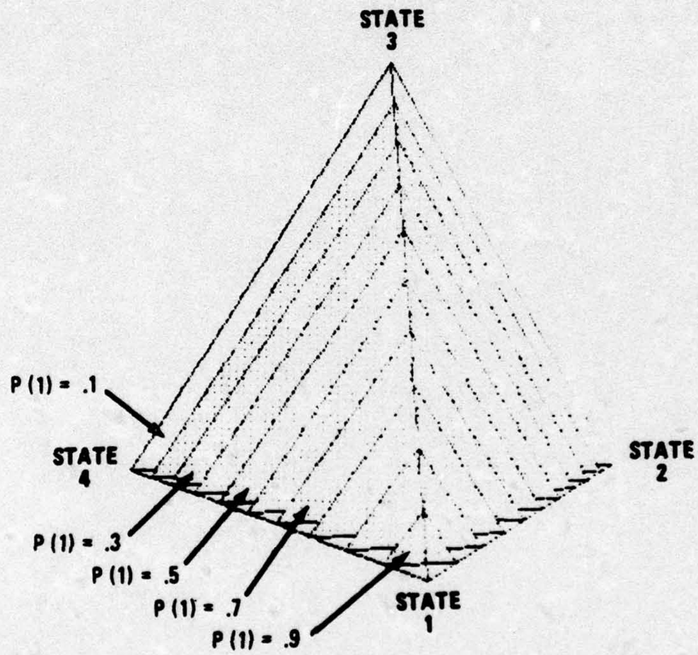


Figure D-5

PROBABILITY TETRAHEDRON WITH PROBABILITY PLANES

In exactly the same way there are planes parallel to the face opposite vertex 2 which represent various probabilities that state 2 will occur (Figure D-6), and there are planes parallel to the two remaining faces which represent the probabilities of states 3 and 4 (Figures D-7 and D-8). Any particular point is thus defined as the intersection of four planes, one in each of four directions, which pass through it.

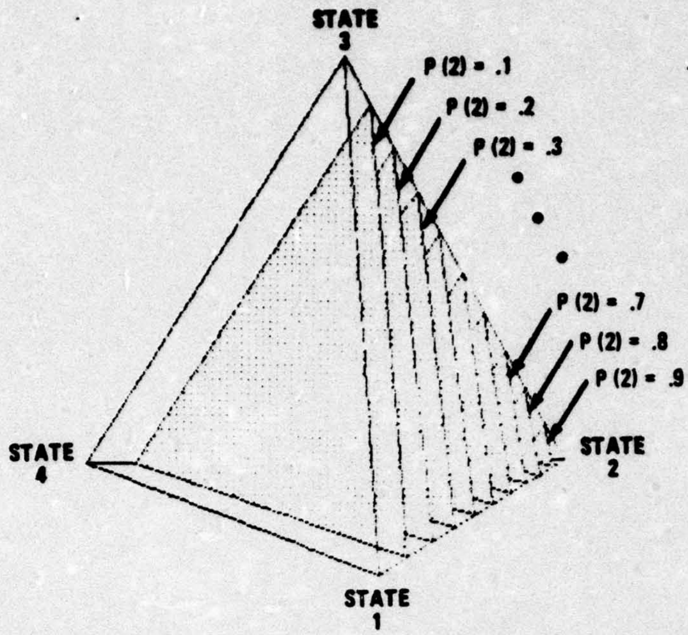


Figure D-6

PROBABILITY TETRAHEDRON WITH PROBABILITY PLANES

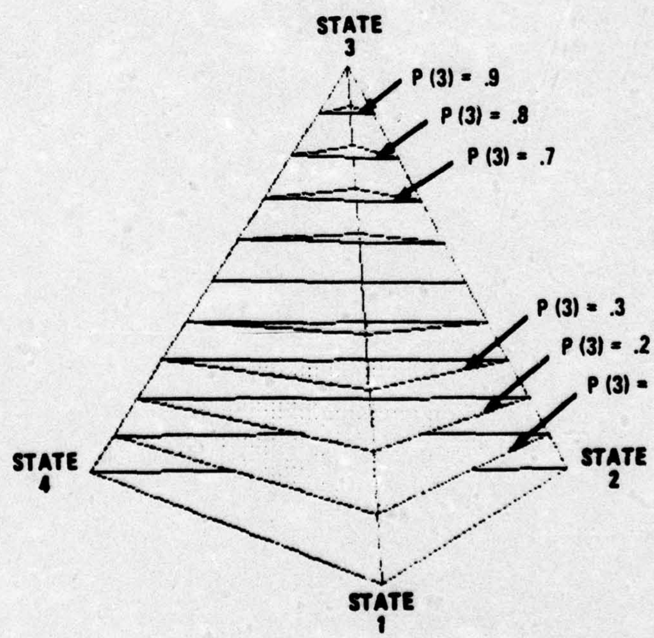


Figure D-7

PROBABILITY TETRAHEDRON WITH PROBABILITY PLANES

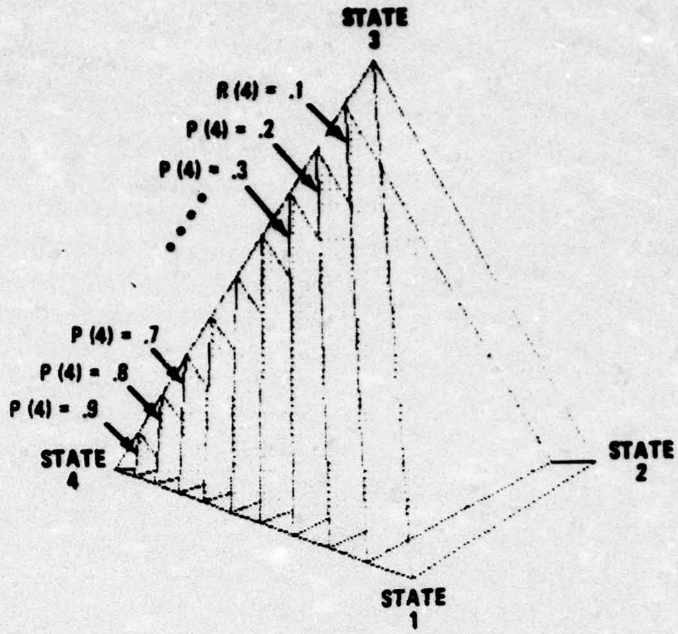


Figure D-8

PROBABILITY TETRAHEDRON WITH PROBABILITY PLANES

For example, the point representing the probabilities p(1) = 0.1, p(2) = 0.2, p(3) =0.3, p(4) = 0.4 is defined by a plane parallel to the face of the tetrahedron opposite vertex 1 and one tenth of the way between the face and the vertex (Figure D-9), a plane parallel to the face of the tetrahedron opposite the vertex marked 2 and one-fifth of the way from the face to the vertex (Figure D-10), a plane parallel to the bottom of the tetrahedron and three-tenths of the way from the bottom to the top (Figure D-11) and a final plane parallel to the face of the tetrahedron opposite vertex 4 and four-tenths of the way from the face to the vertex (Figure D-12).

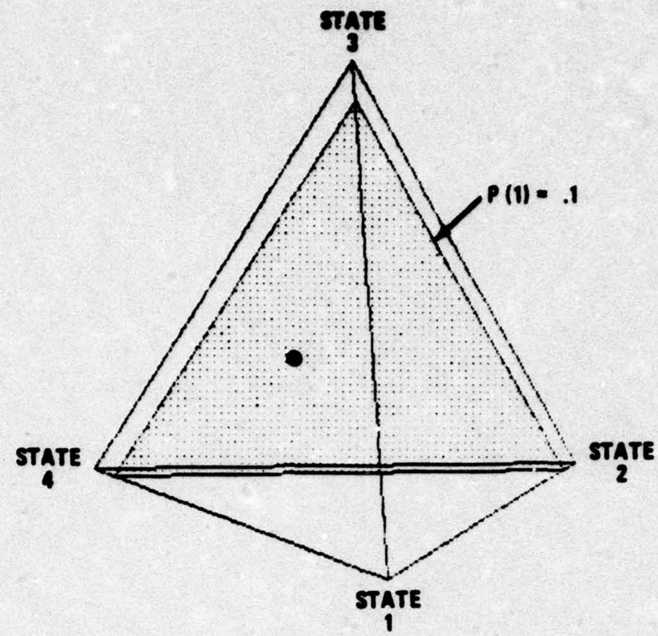


Figure D-9

PROBABILITY TETRAHEDRON SHOWING PROBABILITY BUG DEVELOPMENT

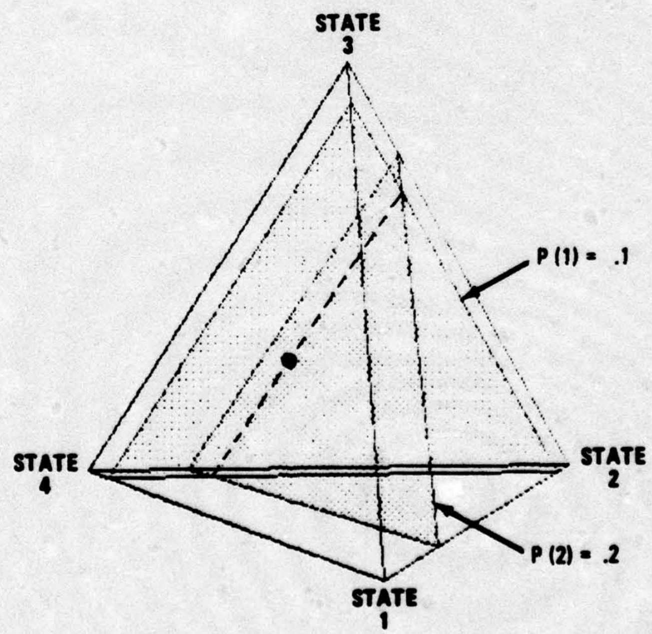


Figure D-10

PROBABILITY TETRAHEDRON SHOWING PROBABILITY BUG DEVELOPMENT

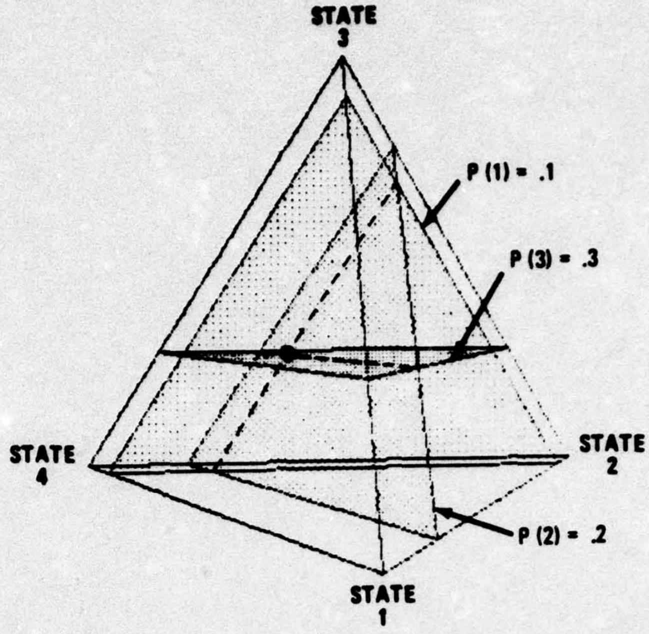


Figure D-11

PROBABILITY TETRAHEDRON SHOWING
PROBABILITY BUG DEVELOPMENT

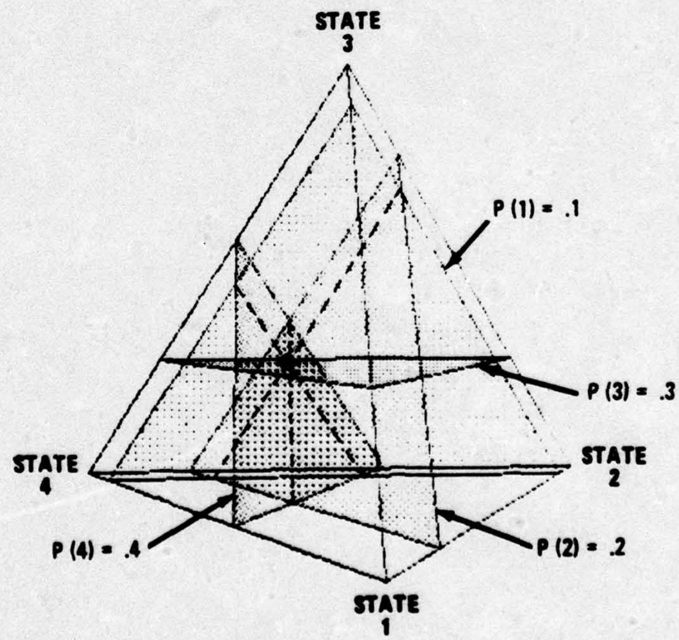


Figure D-12

PROBABILITY TETRAHEDRON SHOWING
PROBABILITY BUG DEVELOPMENT

Another way to describe the position of the probability bug in space is to show the distance of the bug from each of the four faces. In order to get a better view of the bug, imagine that the tetrahedron is turned around on its vertical axis to the right, so that vertex 4 points out of the page, vertex 1 is to the right, and vertex 2 points toward the left. The probability of state 1 is represented by the distance of the probability bug from the face opposite vertex 1, shown as an arrow in Figure D-13).

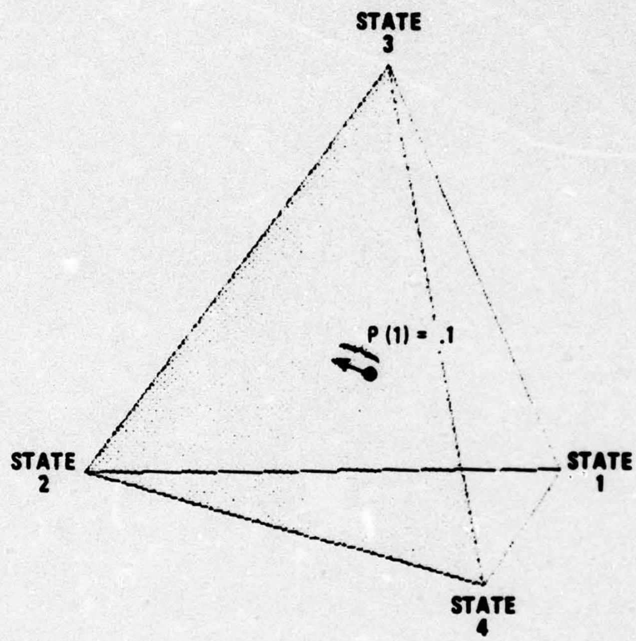


Figure D-13

LOCATION OF PROBABILITY BUG, STATE 1

Similarly, the probability of state 2 is represented by the distance of the probability bug from the face opposite vertex 2 (Figure D-14), the probability of state three by the distance from the bottom face (Figure D-15) and the probability of state 4 is represented by the distance to the face in the back which is opposite vertex 4 (Figure D-16). The location of the probability bug is thus represented completely by the lengths of the four arrows (Figure D-17).

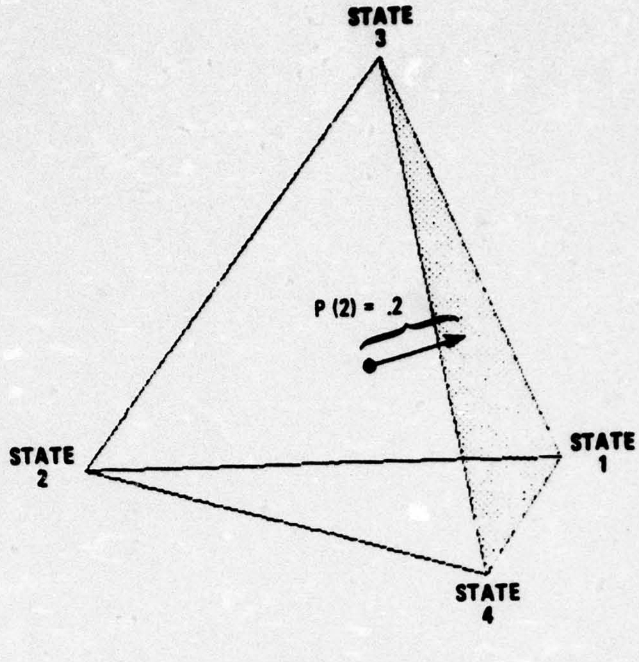


Figure D-14

LOCATION OF PROBABILITY BUG, STATE 2

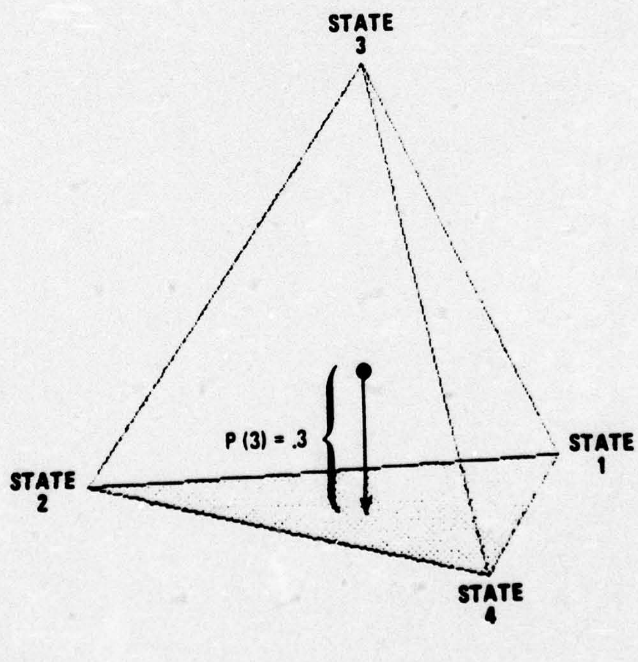


Figure D-15

LOCATION OF PROBABILITY BUG, STATE 3

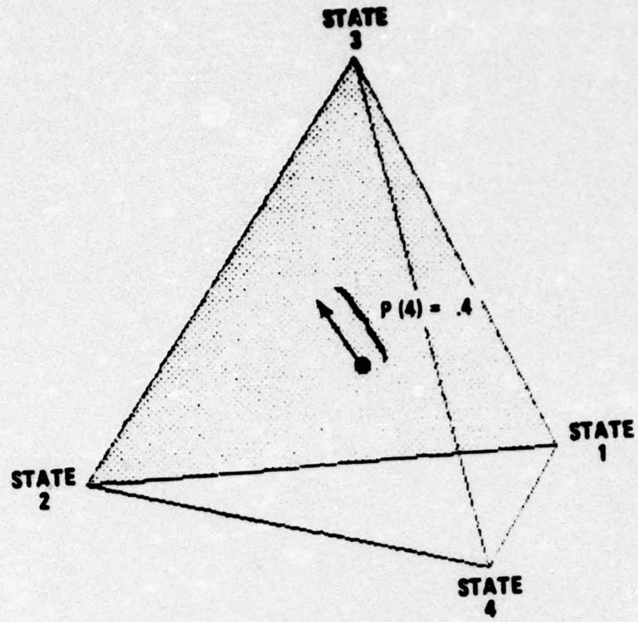


Figure D-16

LOCATION OF PROBABILITY BUG, STATE 4

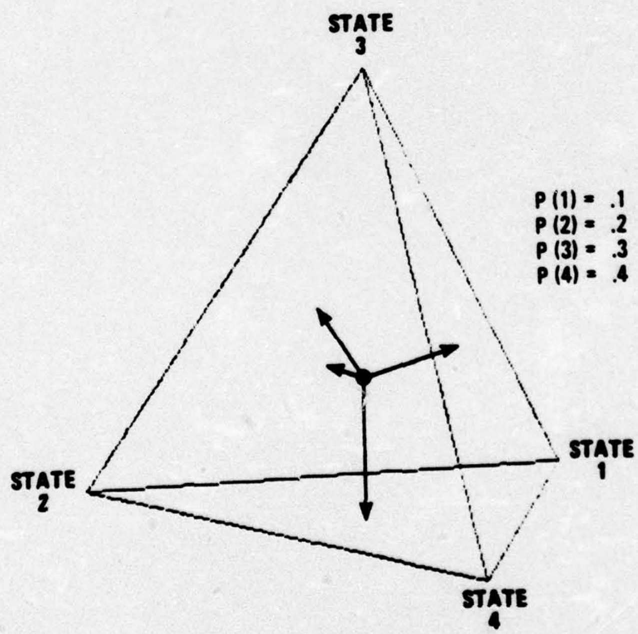


Figure D-17

LOCATION OF PROBABILITY BUG,
STATES 1 THROUGH 4

D.5 Projection Method

The projection display is illustrated for the case of four states and three actions as shown in Figure D-18. The tetrahedron is divided into three action volumes by threshold planes. The plane separating actions A and B passes through the points:

$p(1) = .5, p(2) = .5, p(3) = 0, p(4) = 0;$

$p(1) = 0, p(2) = .67, p(3) = .33, p(4) = 0;$ and

$p(1) = 0, p(2) = .75, p(3) = 0, p(4) - .25.$

The threshold plane between actions A and C passes through the points:

$P(1) = .4, p(2) = 0, p(3) = 0, p(4) = .6;$

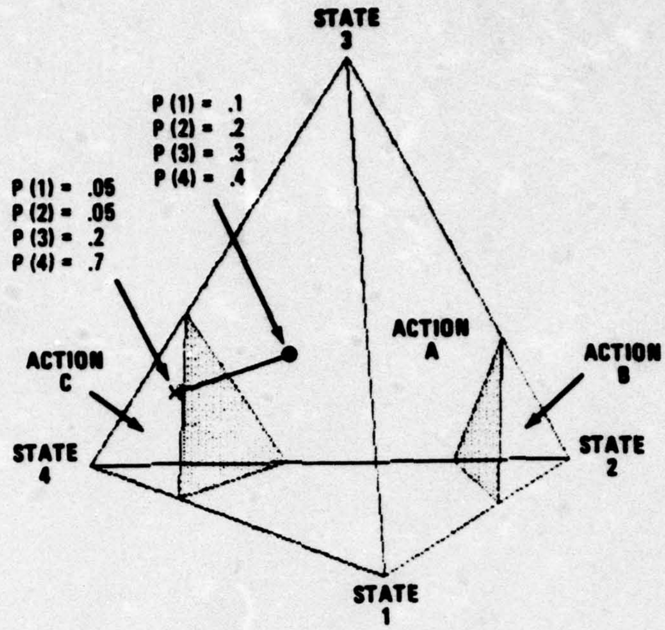
$p(1) = 0, p(2) = .4, p(3) = 0, p(4) = .6;$ and

$p(1) = 0, p(20 = 0, p(3) = .4, p(4) = .6.$

Thus, for the probability point, $p(1) = .1$, $p(2) = .2$, $p(3) = .3$, $p(4) = .4$, action A is preferred, and for the probability point, $p(1) =.05$, $p(2) = .05$, $p(3) = .2$, $p(4) =.7$, action C is preferred.

The projection method consists of displaying the projection of the thresholds and the probability bug onto faces of the tetrahedron. Two of the four possible projections, on the 1-2-3 and 2-3-4 faces, are shown at the bottom of Figure D-18. The projections present the inside of the tetrahedron as it would be seen viewed perpendicularly through these faces.

The main difficulty with the projection method is that the thresholds are not probability lines, as they are in the triangular representation of three states, they are probability bands. This feature sometimes makes it difficult or impossible to tell exactly where the probability bug is and, hence, what the preferred decision is. For instance, consider the 1-2-3 projection on the bottom left of Figure D-18. In this projection, the threshold between Actions A and C appears as a large triangle in the center of the probability triangle. Furthermore, whenever the probability bug is located within the threshold band, it will appear the same, regardless of which action, A or C, is preferred. Thus for the probabilities shown, the action indicator appears the same despite the fact that action A is preferred at the dot, "•" , and action C is preferred at the "X." However, other views may not have this problem, as shown in the 2-3-4 projection. Here it is quite clear that action C is preferred at the "X," and



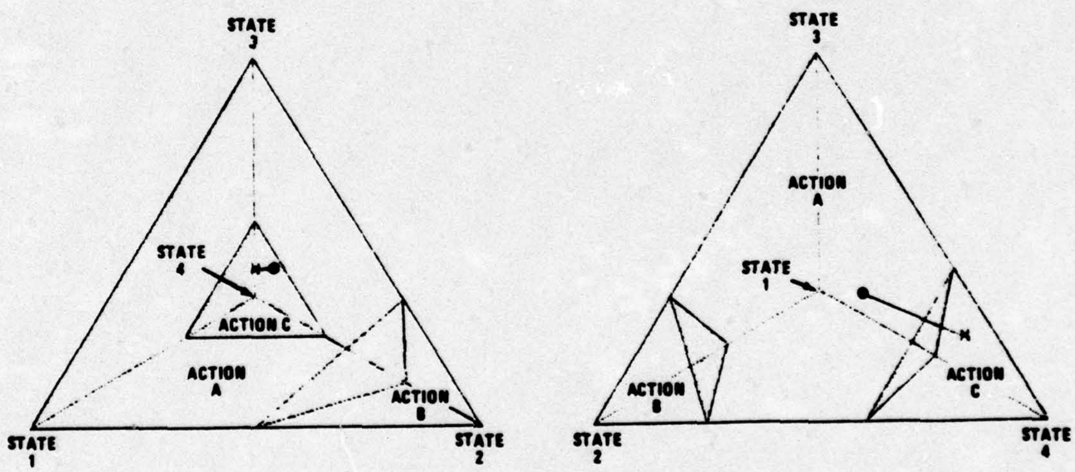


Figure D-18
PROJECTION METHOD

action A at the "dot." It remains to be seen whether this ambiguity presents a problem when actual decisions are modeled. For example, it may be possible to display the path of the probability bug as a dashed line whenever it lies "behind" the threshold plane. In any case, it is clear that use of this method requires careful consideration of the face to be used for projection.

D.6 Cutting-Plane Method

The essence of the cutting-plane method is illustrated in Figure D-19, again using the probability tetrahedron. As noted in Section 3.1.3, the tetrahedron may be described using planes parallel to the faces which pass through the probability point. These planes form the cutting-plane representation at the given probability point. For example, through the point $p(1) = .1$, $p(2) = .2$, $p(3) = .3$, and $p(4) = .4$, the cutting plane parallel to the 1-2-3 face has the equation: $p(4)=.4$ and the cutting plane parallel to the 2-3-4 face has the equation $p(1)=.1$. These cutting planes are displayed at in the bottom of Figure D-19.

Next, let us investigate the threshold representation in the cutting planes. Consider the four-state value table shown in Table D-1, which can be assessed in the manner explained in pages 3-6 through 3-9 of Brown, et al. (1975). From this value table, the following thresholds can be calculated[1]:

A/B Threshold:
$$p(2) = p(1) + p(3) + 2.8p(4)$$
$$p(1) < .5$$
$$p(3) < .333$$
$$p(4) < .263$$

A/C Threshold:
$$p(4) = 1.7p(1) + 1.7p(2) + 1.7p(3)$$
$$p(1) < .37$$
$$p(2) < .37$$
$$p(3) < .37$$

The display of the thresholds in the tetrahedron is shown at the top of Figure D-20, and the intersection of the thresholds with the cutting planes is shown at the bottom of Figure D-20. Thus, in contrast with the projection method, the thresholds in the cutting planes consist of lines, and there is no ambiguity over the position of the probability bug with respect to the thresholds provided that the thresholds appear in the cutting plane. Notice however, that the threshold lines appear in the $p(1) = .1$ cutting-plane, but

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[1]These thresholds are approximately the same as those used in the illustration of the projection method, Figure D-18.

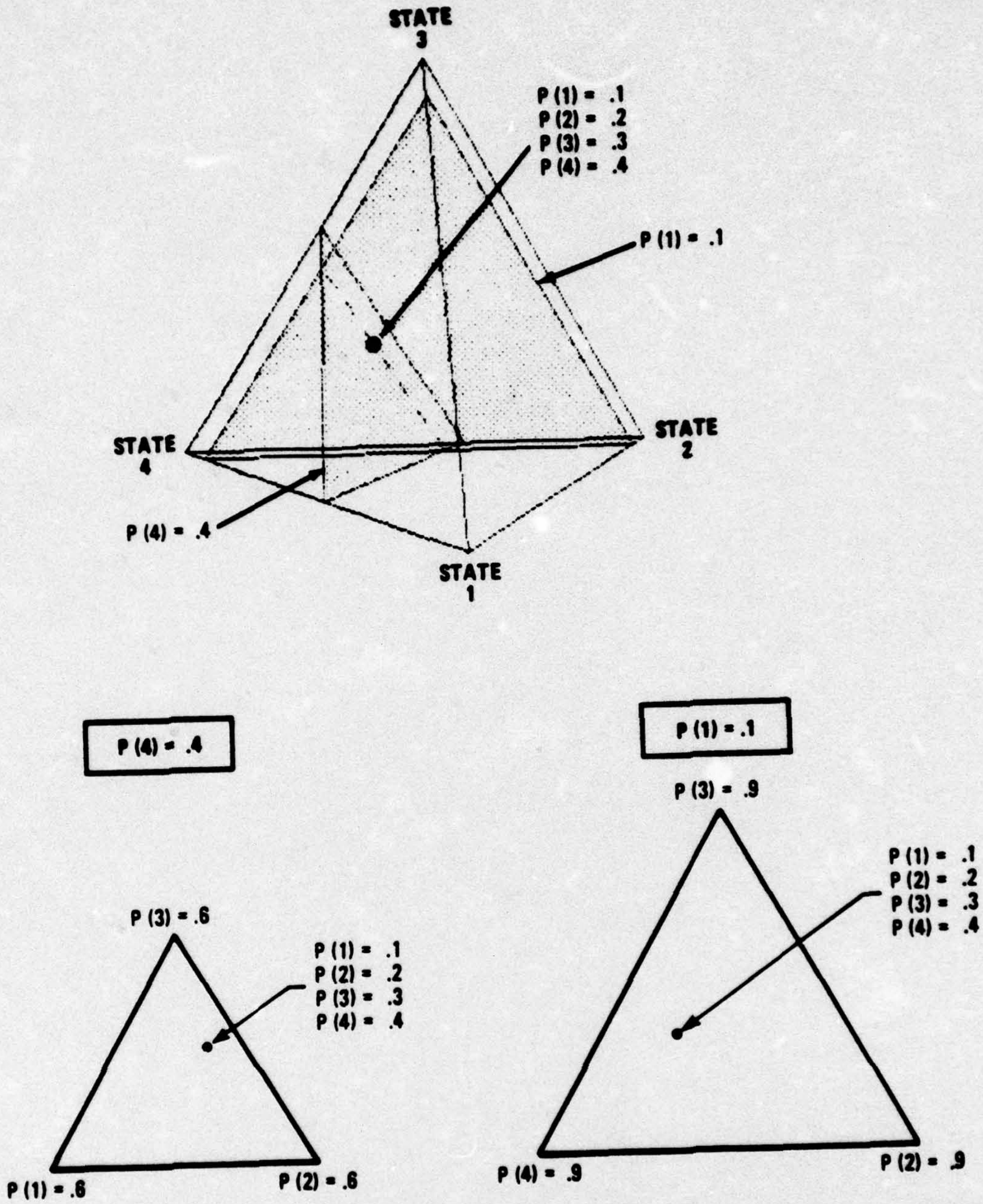

Figure D-19
CUTTING-PLANE METHOD

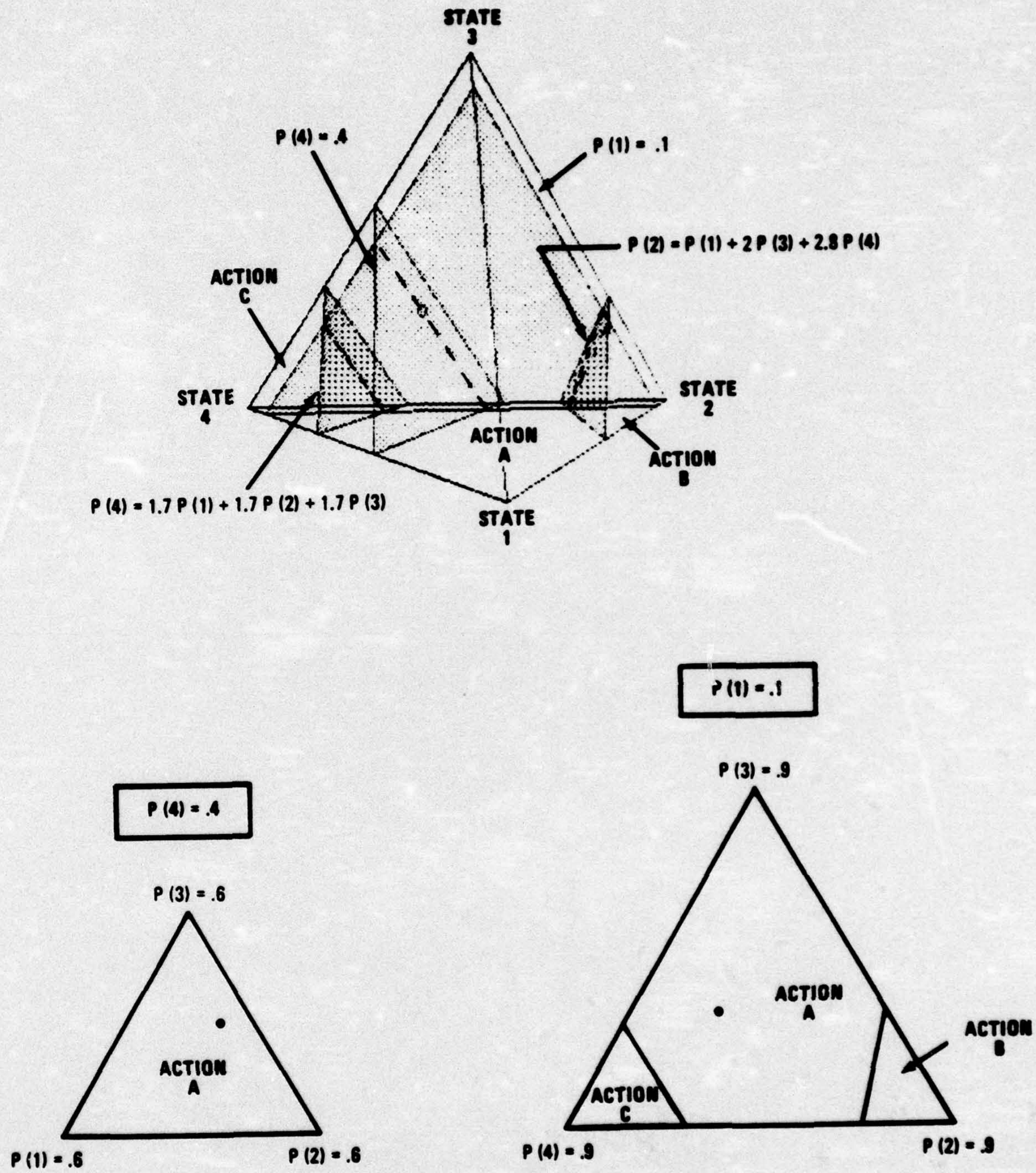

Figure D-20
CUTTING-PLANE METHOD

STATE / ACTION	1	2	3	4
A	0	-25	0	-30
B	-25	0	-50	-100
C	-50	-75	-50	0

<u>A/B Threshold</u>

$$-25p(2) - 30p(4) = -25p(1) - 50p(3) - 100p(4)$$
$$p(2) = p(1) + 2p(3) + 28p(4)$$

<u>A/C Threshold</u>

$$-25p(2) - 30p(4) = -50p(1) - 75p(2) - 50p(3)$$
$$p(4) = 1.7p(1) + 1.7p(2) + 1.7p(3)$$

Table D-1: FOUR-STATE VALUE TABLE

not in the p(4) = .4 cutting plane. This is because, with p(4) = .4, the probability of p(1), p(2), or p(3) could not change enough to cause another action to be preferred. This means that some cutting planes may display essentially no information about thresholds, and this may not be useful to the user. For this reason the choice of cutting planes is very important, as is the choice of the projection face in the projection method.

The thresholds within the cutting planes are calculated from the data in the value table and from the location of the probability bug. For example, the threshold equations for the cutting plane parallel to the 2-3-4 face are obtained by substituting p(1) = .1 in the threshold equations of Table D-1. Figure D-21, at the top left, shows a convenient format for this calculation. First, copy the last three columns of the value table, those relating the actions, A, B, C, to states 2, 3, 4. Next, to each row, add p(1) = .1 times the value for the row shown in the state 1 column in Table D-1 (for example, add .1 x (-25) = -2.5 to each entry in action B row). This calculation yields the value table at the top right of Figure D-21, which can be used to derive the threshold equation illustrated and plotted in the lower part of the figure. The convenience of this procedure is seen when the position of the probability bug changes, for instance, to p(1) = .05, p(2) = .05, p(3) = .2, p(4) = .7. As shown in Figure D-22, this change is accommodated by changing the amount added to each row due to column 1's value.

This probability change is also illustrated in Figure D-23. As shown in the bottom figure, changing only the probability changes both the bug position and the thresholds. In the case of the cutting plane parallel to the 1-2-3 face this probability change caused the entire display to change from favoring action A to favoring action C. The sizes of the cutting planes have also changed, reflecting the change in the degrees of freedom for the remaining probabilities. Thus, the revised cutting plane parallel to the 1-2-3 face allows the three probabilities to vary between 0 and .30, whereas they were formerly free to vary from 0 to .60. This represents a reduction of one-half, and the triangle in Figure D-23 is half as big as it was in Figure D-20.

The cutting-plane method appears to have several attractive properties. It does not force the model to take a constrained form, it communicates the dynamic situation well, and it presents unambiguous threshold lines. The major disadvantage is that any the movement of the probability bug causes the probability location, the threshold locations on the cutting planes, and the size of the tri-

ACTION \ STATE	2	3	4
A	−25	0	−30
B	0	−50	−100
C	−75	−50	0

+

FROM STATE 1
0
−2.5
−5

=

ACTION \ STATE	2	3	4
A	−25	0	−30
B	−2.5	−52.5	−102.5
C	−80	−55	−5

<u>A/B Threshold</u>

$$-25p(2) - 30p(4) = -2.5p(2) - 52.5p(3) - 102.5p(4)$$
$$p(2) = 2.3p(3) + 3.2p(4)$$

<u>A/C Threshold</u>

$$-25p(2) - 30p(4) = -80p(2) - 55p(3) - 5p(4)$$
$$p(4) = 2.2p(2) + 2.2p(3)$$

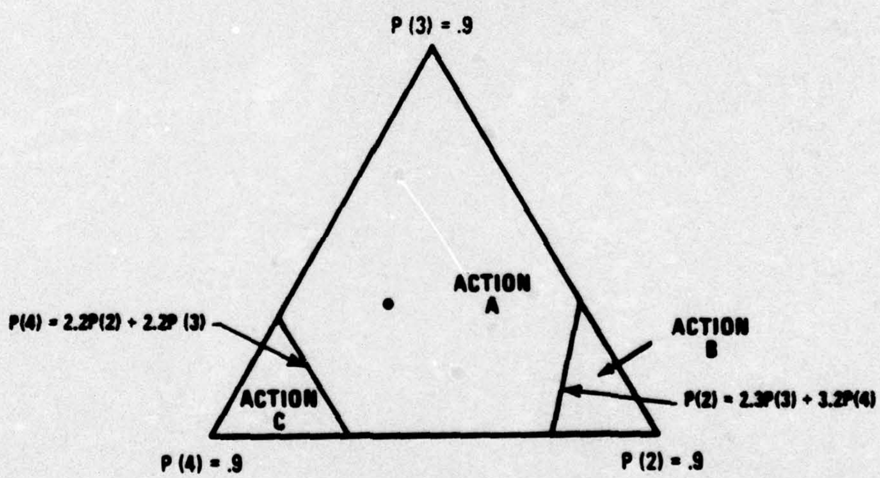

Figure D-21

INITIAL THRESHOLD CALCULATION FOR THE 2-3-4 CUTTING PLANE

STATE / ACTION	2	3	4
A	-25	0	-30
B	0	-50	-100
C	-75	-50	0

+

FROM STATE 1
0
-1.25
-2.5

=

STATE / ACTION	2	3	4
A	-25	0	-30
B	-1.25	-51.25	-101.25
C	-77.5	-52.5	-2.5

<u>A/B Threshold</u>

$$-25p(2) - 30p(4) = -1.25p(2) - 51.25p(3) - 101.25p(4)$$
$$p(2) = 2.2p(3) + 3.0p(4)$$

<u>A/C Threshold</u>

$$-25p(2) - 30p(4) = -77.5p(2) - 52.5p(3) - 2.5p(4)$$
$$p(4) = 1.9p(2) + 1.9p(3)$$

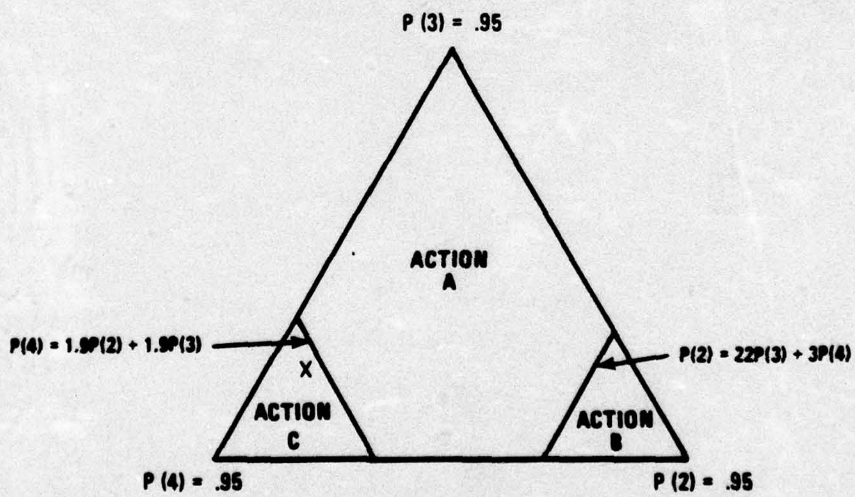

Figure D-22

REVISED THRESHOLD CALCULATION FOR THE 2-3-4 CUTTING PLANE

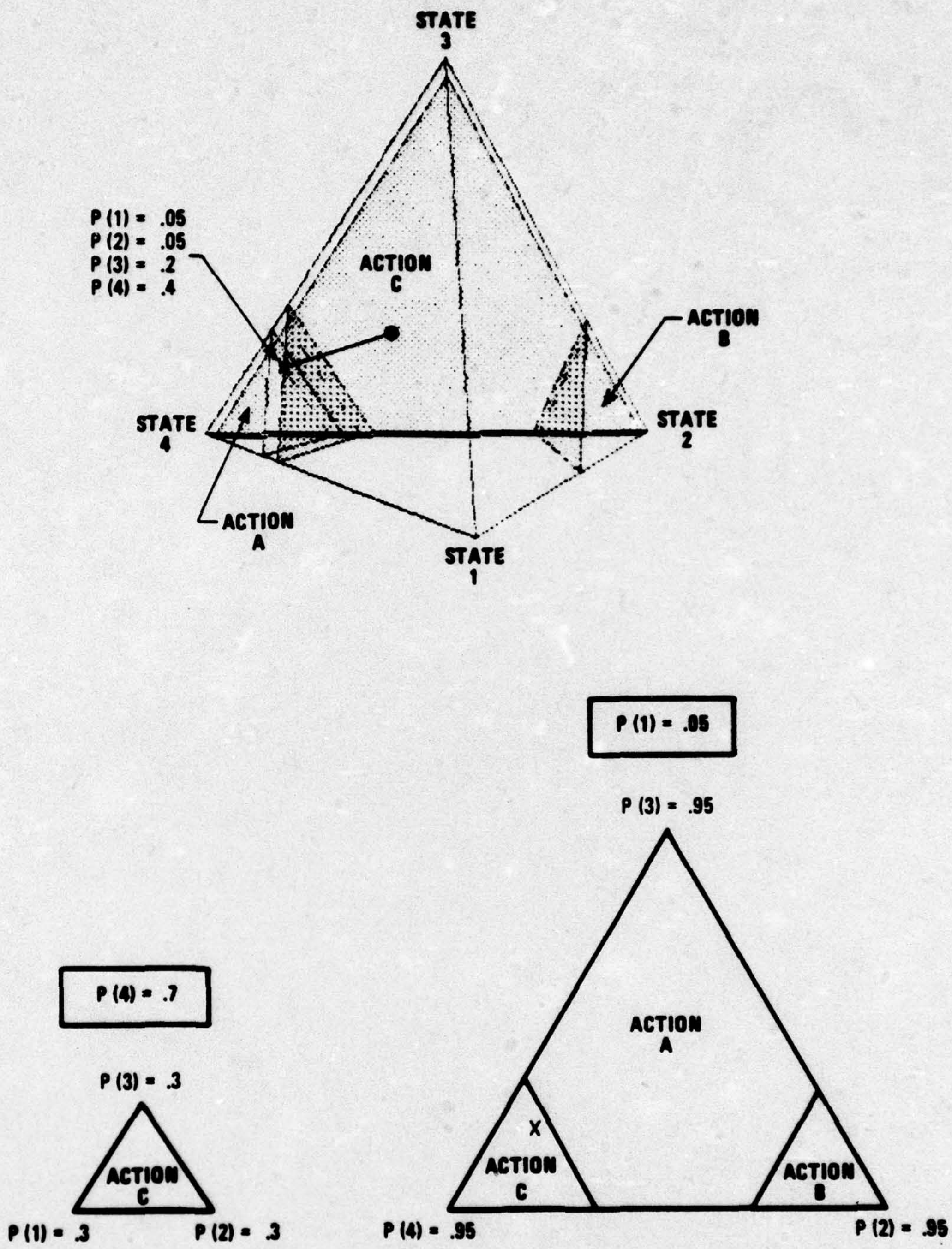

Figure D-23

REVISED THRESHOLD CALCULATION FOR THE CUTTING-PLANE METHOD

angles to change. This is in contrast to the original Execution Aid, in which movement in the probability bug caused only the probability location to change (the threshold locations and the size of the display remained fixed). The changing threshold locations are a problem because they allow for the possibility of surprises. That is, the probability bug may cross a threshold that was not previously displayed, causing a new action to be preferred. Further, the changing sizes of the displays is a potential problem because it may have a somewhat disconcerting effect on a user.

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